

A New Enhanced Binary Ghost Canceling Reference Signal for TV Ghosts

by

Wajih Abdul-Elah Abu Al-Saud

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

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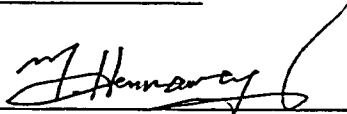
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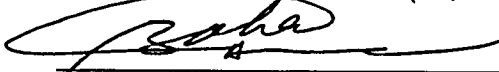
This thesis, written by **Wajih Abdul-Elah Abu Al-Saud** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of

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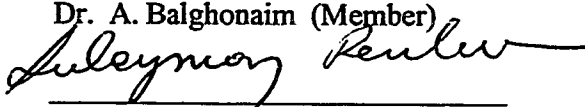
Thesis Committee


Dr. M. S. El-Hennawey (Chairman)



Dr. M. T. Boraie (Cochairman)


Dr. H. Baher (Member)


Dr. A. Balghonaim (Member)


Dr. S. S. Penbeci (Member)


Department Chairman


Dean, College of Graduate Studies

Date: 1/7/96



To my parents, brother, sisters, and to my wife

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Abstract

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Ghost Canceling Reference (GCR) signals have been introduced for the purpose of identifying the characteristics of TV channels. The identification of a certain channel enables removing most ghost components that are introduced in the video signal by the ghost channel. One important feature that is required in a GCR signal is its ability to excite most of the channel modes in order for the receiver to identify the channel completely. Other features are the simplicity of generating it at the transmitter and detecting it at the receiver with the minimum possible hardware, and also simplifying the process of channel identification from the viewpoint of having simple calculations and fast adaptation to channel variations. A new GCR sequence is proposed in this thesis. It is based on a bipolar binary (+1 or -1) GCR signal. This binary GCR enables the receiver end to determine the channel characteristics (transfer function coefficients) in a non-iterative way, which speeds up the cancellation of ghosts. The technique also requires neither multiplication nor division to be performed in the process of channel identification. Only additions and subtractions are required. This feature dramatically boosts the speed of the ghost canceller, lowers its cost, and simplifies its implementation. The identification of the ghost channel using this GCR can be used along with a suitable algorithm to find the optimum tap coefficients of the equalizer which removes the image ghosts. In comparison with existing GCR signals, the proposed approach is seen to be more efficient.

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خلاصة الرسالة

اسم الطالب :	وجيه عبدالإله أبو السعود
عنوان الدراسة :	إشارة مرجعية ثنائية جديدة ومحسنة لإزالة الأشباح من الصور التلفزيونية
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تستعمل الإشارة المرجعية لإزالة الأشباح بهدف التعرف على خصائص القنوات التلفزيونية. هذا وبواسطة التمييز لقنوات الاتصال التلفزيوني فإنه يمكن إزالة معظم مكونات الأشباح التي تضاف لإشارة الصورة بواسطة القناة المسببة للأشباح. ومن المميزات المهمة المطلوب توفرها في الإشارة المرجعية لإزالة الأشباح القدرة على تخفيض معظم أطوار القناة من أجل تمكين المستقبل من كشف قناة الإرسال تماماً. ومن الخصائص الأخرى المطلوب توافرها في هذه الإشارات المرجعية بساطة إنتاجها عند المرسل و يسر استخدامها عند المستقبل بأقل قدرٍ من الدوائر، وإضافة إلى ذلك فإن سهولة عملية كشف القناة بالنظر إلى بساطة الحسابات وسرعة الحصول على التكيف لتغيرات القناة تعد من المميزات المرغوبة.

وفي هذه الرسالة تم اقتراح استعمال إشارة مرجعية جديدة لإزالة الأشباح من الصور التلفزيونية. أهم ما يميز هذه الإشارة أنها ازدواجية الأقطاب بمعنى أن قيمتها إما أن تكون $1+$ أو $1-$ ، ومن ثم يمكن للطرف المستقبل تحديد خصائص القناة دون اللجوء إلى الطرق التكرارية المتوالية، وهذا يؤدي بدوره إلى سرعة إزالة الأشباح. ومن أهم مميزات الطريقة المقترحة للكشف عن خصائص القناة أنها لا تتطلب إجراء العمليات المعقدة حسابياً بما فيها الضرب و القسمة وإنما تحتوي فقط على العمليات الحسابية البسيطة من جمع وطرح فقط مما يؤدي إلى تبسيط الدوائر المزيلة للأشباح وتصميمها تصميمًا اقتصادياً فعالاً. وتقرّح الرسالة استخدام خصائص القناة التي تم التعرف عليها لاستنباط المعاملات المثلى للمعادل والذي يقوم فعلياً بإزالة الأشباح من الصور التلفزيونية.

ولقد أحررت في هذه الرسالة دراسةً مستفيضةً بغية المقارنة بين أداء الطريقة المقترحة و الطرق التقليدية لإزالة الأشباح التلفزيونية، وقد أسفرت نتائج هذه الدراسة عن تميز الطريقة المقترحة وعلو كفاءتها وذلك من حيث جودة الإزالة وأيضاً من حيث اقتصاديتها.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

يونيو ١٩٩٦ م

Chapter 1

INTRODUCTION

While TVs few decades ago were considered as a luxury component in homes, nowadays they became an essential part of almost every household. Modern homes rarely have less than two or three TV receivers. Because of this wide spread, the quality and complexity of TV receivers increased dramatically. When TVs were first invented, they had a very huge tuning system using vacuum tubes along with a primitive Cathode Ray Tube (CRT) that displayed poor quality images usually with blurry edges. Today, TVs became sophisticated receivers that may have very advanced tuning systems for better

quality reception and may use CRTs that do dual scanning per frame for sharper images. The sound quality of TVs also improved to reach the point of having TVs with stereo sound systems or 3-dimensional sound effects. Different types of TV screens were also developed. Nowadays, there exist TVs that don't use the CRT at all but use Liquid Crystal Displays (LCD) instead. TVs may, in the near future, be very thin due the use of LCDs, so they may be mounted on walls. The improvement in the TV field is not limited to TV receivers, but also TV transmitters had their share of improvement to cope with both the enhancements in TV receivers and the consumers' continuous demand for better quality. The improvement of TVs has been a hot issue since it was invented in the early 30's of this century. The part of enhancements that concerns us here is the one associated with the improvement of TV receivers for the purpose of better quality reception.

1.1 PROBLEMS IN TV RECEPTION

Since the invention of the conventional analog TV in the late 1920's and early 1930's, the reception of a good and clear TV picture has been a major concern for TV developers and manufacturers. Since then, TV transmitters and receivers have undergone a lot of improvements to guarantee the best possible reception quality. TV tuners were improved to demodulate received signals with the best retained quality as possible. TV screens have also improved to enhance the displayed image and reduce problems such as blurring to the minimum amount. Enhancements on the TV reception to improve the quality of its displayed images are another challenge. The quality of the received signal at the TV antenna is one of the main requirements for getting high quality displayed images.

When the quality of the received signal is high (i.e. no noise or distortion) clear high quality images can be displayed. However, when the received signal is itself noisy or distorted, then usually a regular TV receiver fails to produce a good quality image even if it is of a high quality brand.

Getting a very clear TV image on TV receivers is not always possible due to some impairments that may corrupt the TV signal as it travels as an electromagnetic (EM) wave between the transmitter and the receiver. An important cause of bad TV reception is the additive (or in some other cases multiplicative) noise that is added to (or multiplied by) the TV signal along its traveling path. Because of the random nature of noise, it is impossible to completely cancel its effect from the received signal. However it can be minimized. So, in most of the cases noise is something that a TV user has to live with and accept. A possible solution to the problem of noise is to change the TV transmission from its conventional analog nature to the digital domain. Although, digital TV systems have their own problems such as the required wide bandwidth, they have the very attractive feature of being robust to noise. The effect of noise on digital transmission can be further minimized by employing error correction algorithms on the received information.

Another type of impairments is due to channel nonlinearity. This phenomenon is seen in frequency selective channels, where the corruption of the signal depends on its frequency contents. Such problems have been widely discussed in the literature, however it is not of our concern in this thesis.

The type of distortion that this thesis addresses is the multipath phenomenon. In multipath reception, a transmitted signal reaches the receiver via many different paths, each having a different length. In TV, roughly speaking, this causes the original image, along with duplicated advanced and delayed copies of it (usually called ghosts), to be displayed on the TV screen.

1.2 BACKGROUND ON MULTIPATH DISTORTION

Part of the power of any EM wave reflects back when it hits the interface between two media having different refractive indices. In most cases, the difference in refractive indices is due to having an interface between different materials. Whenever a transmitted EM wave reaches a receiver via several paths with different lengths (due to reflections), a type of distortion called multipath distortion corrupts the signal. In multipath distortion, the received signal is, in general, made up of the sum of many components. The strongest component of all is called the main path component. In most cases, the main path component is the one that travels along a direct path between the transmitter and the receiver (line of sight). In this case, the main component has the smallest traveling time delay of all received components. However, in some cases the main component may not be that of the direct path. It may reach the receiver by reflection over objects. In this case, components that have a delay smaller than that of the main path will be part of the received signal.

When this multi-component signal is displayed on the TV screen, a strong image along with relatively weak replica of it appear. These weak replica are commonly known as ghosts. The phenomenon of ghosts is very clearly observed in TV images whenever a TV receiver is located in a region suffering from multipath distortion. In most cases, the main path characterized by the strongest signal is the shortest, and all other paths are longer in distance, so the ghosts are delayed attenuated versions of the original signal. In this case, the ghosts are called post-ghosts. Rarely, when the main path is not the direct path between the transmitter and the receiver, while the signal along that path is weaker, the ghost components preceding the strongest image are called pre-ghosts. The problem of TV ghosts is more annoying as the delay between the main path and ghosts becomes larger, and as the relative strength of the ghosts becomes comparable to the main component.

To illustrate the multipath phenomena, Fig. 1.1 shows the transmitted signal reaching the receiver along a direct path and also by reflecting over different types of media. It can be seen that different paths have different lengths and hence each component of the received signal reaches the receiver delayed by an amount proportional to its path length. However, the difference in length between paths is not always the reason of having the multipath problem. Two or more paths may have the same length, but due to the characteristics of the paths, the signal components reach the receiver with different delays. This may occur when refractive indices of different path media are different due to temperature variation, for example, and hence the speed of EM waves is

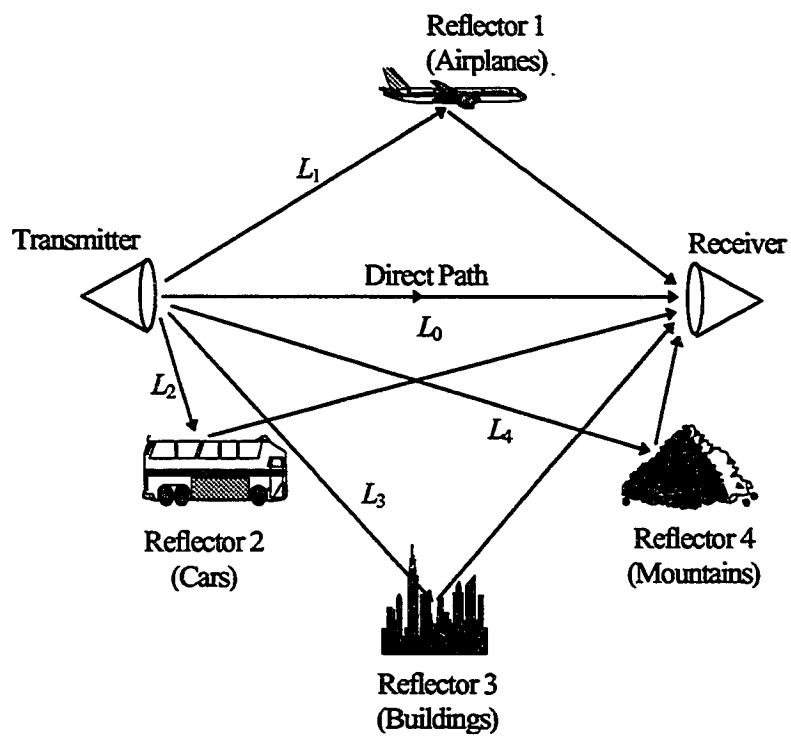


Figure 1.1: The EM wave traveling from the transmitter to the receiver along a direct path and reflecting over different reflectors.

different in these paths. Moreover, a path does not always have a single reflector. There may exist paths where the transmitted signal reaches the receiver after reflecting over two or more reflectors along its traveling path.

If multipath distortion occurs in EM waves intended for audio transmission, such as radio broadcasting, this phenomena is unnoticeable. The reason is that the delay between different paths is usually very small relative to the low frequency of audio signals. However, due to the use of a much higher bandwidth in the case of TV compared to that of audio, and due to the fact that the eye is very sensitive to such problems, the multipath phenomenon is clearly observed on TV receivers. This can be further illustrated by noticing that a certain delay between two components represents a very small phase difference in low frequency, while it may represent a very large phase difference in the case of high frequency signals.

Regions near natural obstacles such as mountains or artificial obstacles such as buildings suffer from the multipath phenomenon. The buildings or mountains are not the only cause of multipath distortion in EM waves. Metallic bodies such as cars, and water surfaces such as lakes (water becomes a very good reflector for EM waves at high frequencies) also reflect EM waves causing multipath distortion. The problem of multipath distortion becomes severer if one reflector or more is not stationary. If a reflector moves with a certain velocity with respect to the transmitter and receiver such as reflections over a moving car or a flying aircraft, then the channel becomes a time varying multipath channel. A less severe time-varying channel occurs due to weather variations.

1.3 BACKGROUND ON TV GHOST CANCELLATION

For several decades, research on the multipath phenomena has been, and continues to be, very active. Several solutions have been proposed to address this problem. The part of this problem related to TV reception, usually called TV ghost cancellation, was first investigated about two decades ago. The first reference in hand talking about ghost canceling goes back to 1979 by Ciciora, et al [1]. As such, TV ghost canceling is not considered a new field of study. However, over the past two decades, ghost canceling systems came a long way from where they originally started. The first TV ghost canceling systems developed were stand alone very bulky and expensive devices with relatively low performance and required continuous manual adjustments. Needless to say, these ghost canceling systems had a very poor market performance.

Significant improvement has been achieved to date in ghost canceling systems in order to improve their performance and minimize their size and cost. Recent research on enhancing the performance of ghost canceling proposed not only the improvement of the ghost canceling device itself, but, it also suggested an enhancement to be done on the transmitted TV signal in a way to give the deghosting device a simple method of identifying the ghosting channel characteristics effectively. The enhancement that is usually made on the TV signal before transmission is the addition of a certain signal waveform that is well known to the transmitter as well as the receiver. This inserted signal

traveling through the ghosting channel suffers from the same distortion the TV signal experiences. When it is detected, the receiver can, by comparing the original known signal and the received corrupted one, identify the characteristics of the corruption which happened to the TV signal and hence retrieve the original TV signal at least partially. The receiver does this by rectifying the effect of the ghosting channel. Due to the lack of such a signal that is known to the receiver, old ghost canceling systems required continuous manual adjustments. The TV user had to make adjustments manually and observe the improvements on the quality of the displayed TV picture.

As stated previously, ghost canceling systems, nowadays, depends on a modification in the transmitted signal to help them deghost the received TV signal. The required modification is the insertion of a certain signal component in a certain location of the TV signal. This signal is known to both the transmitter and the receiver. Such signal is known as the Ghost Canceling Reference (GCR) signal. Since it is known to both the transmitter and receiver, then any corruption that happens to it due to the ghosting channel can be deduced at the receiver end. If the receiver determines how the transmitted signal is corrupted, it may be able to inverse the process performed by the ghosting channel by the use of a proper deghosting equalizer.

Not any GCR can serve as a good identification tool for the characteristics of ghosting channels. Certain characteristics have to be incorporated in the GCR for it to be optimum in the sense of best being able to identify the ghosting channel. Some of the characteristics that are usually required in a signal to serve as a GCR are the flat spectrum,

the equal eigenvalues of the auto-correlation matrix, and the relatively high energy contained within it. Such characteristics allow the GCR to identify all channel modes. They speed up the convergence of the system, and give it immunity to additive noise. One more required characteristic that may contradict with the previous requirements is the simplicity in its shape to allow easy generation, transmission, and detection. Furthermore, the simple shape allows the use of simple calculations for ghosting channel identification. The GCRs proposed in the literature usually try to satisfy as many of these characteristics as possible. However, satisfying all the requirements is very hard if not impossible. So, the GCR to be used in a certain TV system is designed as to have certain characteristics that are more important than others for that particular deghosting system.

1.4 LIMITATIONS OF EXISTING GCRs

Previously proposed GCR sequences are usually one of two forms, either sinusoidal waveforms with a varying frequency that sweeps the frequency range of the TV channel bandwidth [2, 3, 4, 5], or a flat spectrum pseudo random waveform [6, 7]. These two waveforms are selected as to have an almost flat frequency spectrum in the frequency band of the TV signal. As stated previously, the flat spectrum is a desired feature in GCRs. However, all previous ghost canceling systems suffer from complexity due to the selection of these two forms of GCRs. The channel deghosting process performed by such deghosting systems involves a large number of computations and requires a huge amount of hardware.

A further limitation of GCRs proposed in the literature is that they are used to identify the channel recursively. A recursive adaptation process is fast only if the GCR has an auto-correlation matrix with equal eigenvalues. The generation of these GCRs at the receiver is also essential due to the nature of the channel identification algorithm. These features are added limitations on the design of optimum ghost canceling systems.

1.5 MOTIVATION FOR THESIS RESEARCH

As mentioned earlier, some previous research has been devoted towards reaching system optimality by selecting the GCR signal as a pseudo random or a frequency varying sinusoidal waveforms. The selection of the GCR in this way complicates the procedure of identifying the channel impulse response at the receiver. Needless to say, the generation of such GCRs at the transmitter and regeneration at the receiver is difficult.

Because of the limitations and difficulties encountered with previous GCRs, a new form of reference signal is proposed in this thesis. In order to overcome the hardware complexity, a special form of bipolar binary GCR waveforms is selected. The transmission of a binary GCR signal makes the procedure of channel identification a much easier task. Knowing that the transmitter has sent a binary sequence of +1's and -1's makes it very easy for the receiver to identify the modes of the channel with only addition/subtraction operations without the use of multiplication/division operations. This also decreases the requirements on the microprocessor used, where less memory is required for storage of

operands. Three benefits are obtained from using the above GCR: (1) the speed of the deghosting process is increased, (2) the deghosting system becomes simpler, and (3) the system hardware requirements are minimized. Moreover, the overall deghosting performance is improved.

1.6 PROPOSED GCR SIGNAL

In this thesis, our proposed GCR has a much simpler shape than previously proposed GCRs. It is a bipolar binary signal (having the values of either +1 or -1) arranged in a certain sequence. Because of the use of binary values for this GCR, it does not have a flat frequency spectrum, so it is considered to be a sub-optimum GCR from the viewpoint of identifying all channel modes equally. However, due to having only the two values of +1 and -1, it can carry the maximum amount of energy where it has an RMS value of unity, it is simple to generate at the transmitter, and simple to detect at the receiver. Moreover, due to its binary shape and due to the selection of occurrences of the positive and negative binary values, it allows the identification of the ghosting channel with the simplest and lowest possible calculations and hence hardware components.

The amount of calculations required for the ghosting channel identification using a certain GCR specifies the complexity, the speed of channel identification and as such the speed of the ghost removal. Since the overall cost of ghost canceling systems is proportional to their complexity, then the use of the minimum amount of calculation is preferred. The type of calculations required is also an important issue in determining the

complexity and cost of the ghost canceling systems. Since the multiplication and division operations require more clock cycles in a micro-processor environment and more memory elements, they are usually not preferred. The calculations used to identify the ghosting channel using the proposed GCR are only a limited number of additions and subtractions. No multiplications or divisions are required for channel identification when the proposed GCR sequence is used. However, some multiplication and division operations are needed in this deghosting system in the optimum deghosting equalizer design stage.

The feature of having equal eigenvalues of the auto-correlation matrix of a GCR is required if the adaptation process is recursive, where this feature speeds up this process. Although, the proposed GCR does not satisfy the condition of having equal eigenvalues of the auto-correlation matrix, the fact that the channel is identified in a non-recursive way by this ghost canceling system eliminates the requirement of this feature in the GCR. Detailed presentation of the proposed GCR as well as the procedure to finally deghost TV images are included

1.7 THESIS OUTLINE

In Chapter 2 of the thesis, previous work in the field of ghost canceling is reviewed. The different research streams of TV ghost canceling are individually discussed in details, and emphasis is given to the stream discussing the design of GCRs. At the end

of this chapter, other communication fields related to ghost canceling are briefly outlined and compared to TV ghost canceling.

In Chapter 3, a review of the characteristics and requirements for obtaining successful ghost cancellation is given. Following this, the different steps required for the design of ghost canceling systems are discussed.

Chapter 4 presents the proposed ghost canceling system. The first part of this chapter explains the algorithm by which this system identifies the ghosting channel and then designs the ghost canceling filter. The effect of changing the system parameters and their proper selection for optimal operation is also discussed in Chapter 4. The second part of the chapter deals with the characteristics of the proposed system as compared to previous ghost canceling systems.

Chapter 5 provides the results of simulations of the proposed deghosting algorithm and extensive comparisons with the performance of other ghost canceling algorithms then follow. Finally, chapter 6 gives some conclusions and recommendations for further research on the proposed ghost canceling system in particular and on ghost cancellation in general.

Appendices at the end of the thesis give listings of the simulation programs along with their flow charts.

Chapter 2

LITERATURE REVIEW

Since the invention of the conventional TV, significant research has been conducted towards enhancing the quality of the TV reception. The proposed high definition TV, for example, is intended for getting higher quality TV images. Part of the work done in this regard was devoted to TV ghost canceling. Ghost canceling started in the 1970's, and it is still a hot issue of research today for both analog and digital TV systems.

2.1 INTRODUCTION

Although different ghost canceling research in the literature concentrated on different system features, in the field of TV ghost canceling it is very hard to separate one research field from another. For a ghost canceling system to be optimum, every single part in this system has to be optimized. An enhancement in only one feature of a ghost canceling system enhances the performance of the whole system but cannot make it the most optimum unless other system features are also optimized.

2.2 RESEARCH STREAMS OF GHOST CANCELING

The work done up to date in the field of TV ghost canceling branch into several streams. The major streams of the work done in the literature can be categorized into four different research streams. The first research stream tries to find the best ghost canceling filter model that best reverses the TV ghosting processes. The second stream tries to improve the adaptation techniques used to find the optimum set of tap coefficient of the deghosting filter. The other two research streams are the simplification of the hardware requirements to implement different deghosting algorithms, and the design of the most optimum Ghost Canceling Reference (GCR) signal. This chapter reviews the literature and discusses the developments made in the previous four major research streams. The advantages and disadvantages of developments proposed in the literature are also discussed in this chapter.

2.2.1 Modeling the Deghosting Filter

The research outcomes presented in the literature proposing deghosting filters suggest the use of two major deghosting filter models. These two major deghosting filter models are namely, the Infinite Impulse Response (IIR), and the Finite Impulse Response (FIR) models [8]. Real channels are theoretically modeled with an IIR filter model, and as such require an IIR deghosting filter to be deghosted perfectly. The use of an FIR realization [8] of the deghosting filter is simple, but a relatively large filter length is needed to remove the ghost completely due to the need of a large number of filter taps for each channel pole. Also, some ghosts that are characterized by a very long delay cannot be removed if an FIR filter is used unless a very long delay is used along with it [8]. These limitations of the FIR filter cause the complexity of implementation to be relatively high. If, however, an IIR filter is used, the number of required coefficients becomes much less than that of an FIR [8]. This causes a reduction in the system complexity from the viewpoint of the number of required calculations, specially multiplications, needed for channel impulse response identification and deghosting filter adaptation. It is also seen [9] that if an FIR filter is used, then its suppression to the ghosts decreases as the strength of the ghost components approaches that of the original signal until the suppression reaches zero when the ghost and the original signal have the same strengths. This, however does not occur with an IIR, where it is able to remove ghosts even if they have strengths of exactly the same level as that of the main path component [9].

If an IIR is used, other problems may emerge. The stability issue, for example, is one of the major problems associated with IIR filter design, where it becomes a must to assure the stability of the IIR filter after each step of the deghosting channel adaptation [8]. Such an issue is not required with FIR filters due to their unconditional stability. An advantage of the FIR filter over the IIR filter that is worth mentioning is the ability of the FIR to remove the pre-ghosts using a short filter [8]. Another advantage of FIR filters is their better performance over IIR filters in the presence of noise [9]. This is seen by comparing the noise enhancement, which is defined as the ratio of the amount of noise at the filter output to the amount of noise at its input, of the FIR with the noise enhancement of the IIR. The noise enhancement of the FIR filter is given by the equation [9]:

$$N_{out} / N_{in} = [1 - (U / D)^M] / [1 - (U / D)], \quad (2.1)$$

where N_{in} and N_{out} are, respectively, the noise powers at the input and output of the filter, M is the number of taps of the filter, and U / D is the ratio of the undesired voltage representing a single ghost to the desired signal voltage representing the main path component. However, the noise enhancement of the IIR filter is given by [9]:

$$N_{out} / N_{in} = 1 / [1 - (U / D)]. \quad (2.2)$$

It is seen from the noise enhancements of the FIR for any equalizer size M and the enhancement of the IIR that noise suppression of the FIR is larger (i.e. the output noise is

smaller for the same amount of input noise). Moreover, to combat the problem of having a long FIR transversal filter with a very large number of taps for longer delays, Kouam and Palicot [3] proposed the use of small Fast Fourier Transforms (FFTs) by means of a decimation technique for deghosting ghost components having long delays.

2.2.2 Enhancement of Adaptation Techniques

It is required from any ghost canceling system that it adapts to the ghosting channel as fast as possible and to reach the minimum channel coefficients error at the end of the adaptation process. The second research stream is the enhancement of adaptation techniques to reach the goal of finding the filter coefficients with the simplest equipment, fastest convergence speed, and minimum channel coefficients error. Yong and Markhauser [2] discussed the use of iterative Least Mean Squares (LMS) algorithms for the computation of TV ghost canceling system parameters. They tested three recursive forms of LMS learning algorithms for the calculation of the FIR filter coefficients used for TV ghost canceling. The three algorithms tested are:

- (1) the Stochastic Gradient fixed-step (SGLMS),
- (2) the Stochastic Line Search or Carlos Davila (SLS-CD) adjustable step algorithm, and
- (3) the Recursive Modified Gram Schmidt (RMGS) algorithm.

The three algorithms [2] mentioned above are implemented using a test signal that is a sinusoidal waveform with a linear frequency variation. The adaptation of tap weights

of the system according to the SGLMS algorithm follows the adaptation formula [2] given by:

$$c(t+1) = c(t) + \mu [d(t) - c^T(t) x(t)] x(t), \quad (2.3)$$

where $c(t)$ represents the coefficient vector at time t , $x(t)$ is a vector containing the received data, $d(t)$ is the desired value at time t , and μ is the adaptation step size which controls the speed of convergence of the algorithm and its stability. To obtain the best results from this algorithm, the data vector $x(t)$ should be uncorrelated over time. It is shown in [2] that the convergence of the SGLMS is very slow requiring about 7000 samples corresponding to about 100 μ s to reach a very small deghosted output error. To overcome the weakness of the relatively slow convergence of the SGLMS, especially when the correlation of the training sequence is not zero for lags other than zero, Yong and Markhauser [2] proposed more complicated LMS algorithms. The SLS-CD algorithm [2] uses a different adaptation formula. The major difference between the SLS-CD and the SGLMS algorithms is that while the step size of the SGLMS is constant for the whole adaptation process, it is variable in the adaptation processes of the SLS-CD algorithm. The adaptation of the SLS-CD algorithm [2] follows the equation:

$$c(t) = c(t-1) + \alpha(t) y(t), \quad (2.4)$$

where $c(t)$ is the coefficient vector at time t , $y(t)$ is a vector containing the received data, and $\alpha(t)$ is an automatically adjusted adaptation step size. The optimum value of adaptation step size is selected [2] according to the formula:

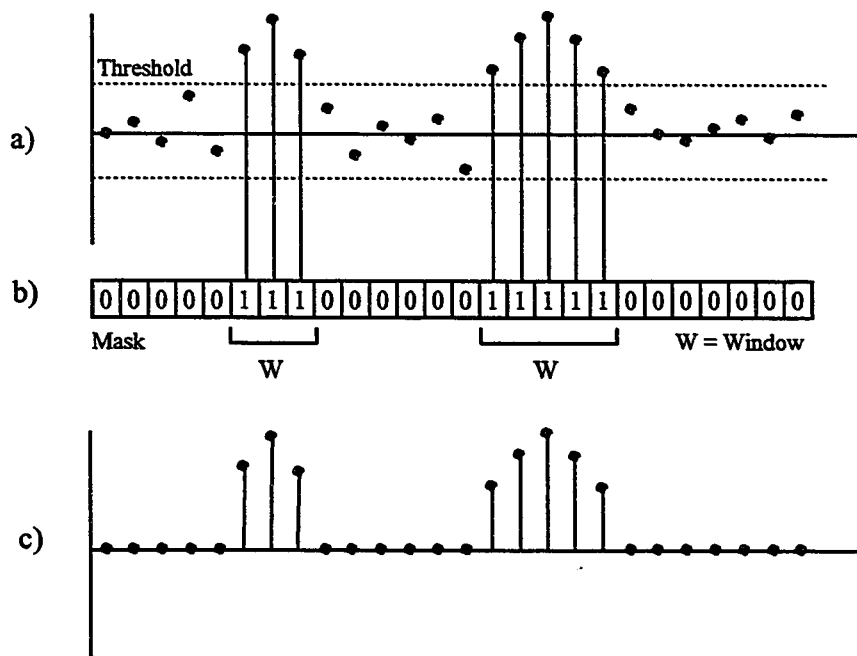
$$\alpha(t) = [p^T(t) y(t) - y^T(t) R(t) c(t-1)] / [y^T(t) R(t) y(t)], \quad (2.5)$$

where $p(t)$ is the cross-correlation vector, and $R(t)$ is the auto-correlation matrix. This algorithm gives a convergence rate that is about four times faster than that of the SGLMS algorithm [2]. However, the price paid for getting a faster convergence is the increased amount of computations required for calculating the step size $\alpha(t)$ at every adaptation step. The RMGS algorithm is a much more complicated process than both of the previous two algorithms. The RMGS performs a Least Squares (LS) estimation to find the tap coefficients. While this algorithm has a very fast convergence speed, its computational complexity is very high [2].

The results obtained in [2] indicate that the SGLMS is simple in implementation but its convergence rate is slow. However, although the SLS-CD has a relatively small increase in the complexity over the SGLMS, it converges faster and has a robust stability. The RMGS algorithm is very fast in convergence but it is computationally complicated [2], hence preventing its implementation in commercial TV ghost canceling systems due to its high implementation cost. The first two LMS algorithms clearly suffer from the relatively long time required to converge to the optimum set of coefficients of the deghosting FIR filter, but they have a simple construction, while to get a much faster

convergence, the complexity increases dramatically as it is the case with the RMGS [2]. Therefore, in general, LMS algorithms suffer from being either slow simple algorithms or fast but very complicated.

Solutions to the relatively slow convergence of the simple types of LMS algorithms, and the other computationally exhaustive fast LMS algorithms are also proposed in the literature. A solution is presented by D'Alto, et al [8] by implementing an LMS based technique called the Advanced Cluster Detection Variable Factor (ACDVF). Their technique is designed so that it removes ghosts regardless of the reference signal used, relatively reduces the number of multiplications required and hence the system complexity, and increases the deghosting speed compared to simple LMS algorithms. Instead of spending time for updating all deghosting equalizer coefficients, even if they are nearly zero, this system identifies the most significant filter coefficients and updates them only [8]. Updating this reduced number of coefficients reduces the amount of computations needed and speeds the convergence rate. The algorithm discussed suggests doing thresholding on a set of coefficients to produce a smaller coefficient set. Only coefficients larger than the threshold are selected. Windowing is then performed according to the results of thresholding to define the set of large coefficients. Only this small set of coefficients is adaptively updated to produce an estimation of the channel until the output error becomes smaller than a certain value, while the remaining coefficients are set to zero [8]. Fig 2.1 shows the process of thresholding and windowing in the ACDVF algorithm.



a) Threshold application to the Coefficients

b) Windowing Process

c) Results not-null weights to be adaptively updated

Figure 2.1: Coefficient set optimization using a windowing technique [8].

According to D'Alto, et al [8], the proper selection of the small set of coefficients decreases the amount of calculations required for the deghosting process. To speed up the adaptation of this algorithm further, a variable step size can be used. The step size can be varied as a step function where it has either a large value for large output error or a small one for small error values. Another approach for changing the adaptation step size is to vary it as a piecewise linear function where it has a large value for large output error, and as the error decreases, the adaptation step size decreases linearly according to pre-defined adaptation paths [8]. Nevertheless, this system suffers from some complexities in the adaptation step size selection. Because of the selection of a smaller number of coefficients to be adjusted while setting the remaining coefficients to zero, this system also suffers from producing imperfectly deghosted images.

2.2.3 Simplification of the Hardware Requirements

Many deghosting algorithms produce good results in principle, but in practice, it is hard to implement them in real-time and real systems because they require very heavy computations, need relatively large space if integrated on IC chips, or because their implementation is very expensive. Ghost canceling systems in the past used to be very expensive and bulky devices. They also require continuous and necessary manual adjustments. As such, they usually had a poor market performance. To overcome these problems, Johnson, et al [4] suggested an approach to modify old ghost canceling systems. Their system uses existing TV receivers and VCR's. The VCR provides a video input signal to the modified ghost canceling system and the ghost canceling system provides the

deghosted video signal to the TV. As such, the demodulation process is not part of the deghosting system. These proposed modifications reduce the cost and complexity of old ghost canceling systems but, the system still has a bulky size and the complexity of the modified system is still high due to the need for a VCR. The advantage gained from this modification is that it serves as an enhancement to already existing manual ghost canceling systems, hence reducing the cost of replacing old systems to a portion of the cost of new systems. Another ghost canceling system already implemented on a CMOS chip occupying a size of 12.3 mm by 12.5 mm is presented by Suzuki, et al [10]. The cost of this compact system is approximately the same as other deghosting systems, but its size is much smaller. It consists of a 398-tap transversal equalizer filter divided into a 48-tap near-by block and a 350-tap far block. The use of this filter chip decreases the size of the ghost canceling system to about 30% of the size of its conventional competitors [10], hence possibly integrating it in small portable TV systems. This system has the problem of relatively complicated structure.

2.2.4 Design of the Optimum GCR Signal

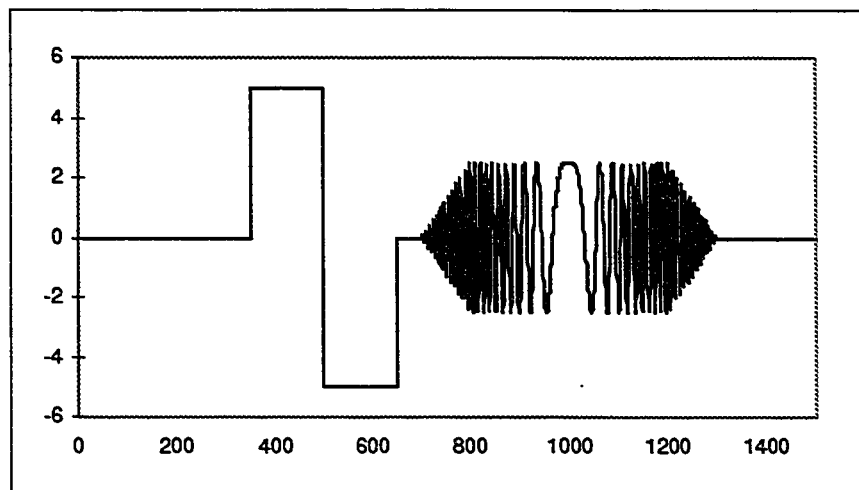
A GCR signal should be able to excite the largest number of channel modes, and should practically be generated at the transmitter and detected at the receiver with minimum hardware. In addition, the GCR should be used to reveal the channel characteristics with the minimum amount of computations. For these reasons, several GCR signals with different shapes and different characteristics have been suggested. Kouam and Palicot [3] proposed a complex exponential signal called the complex

wabulation to be used as a GCR. The mathematical formula of the complex wabulation signal is given by:

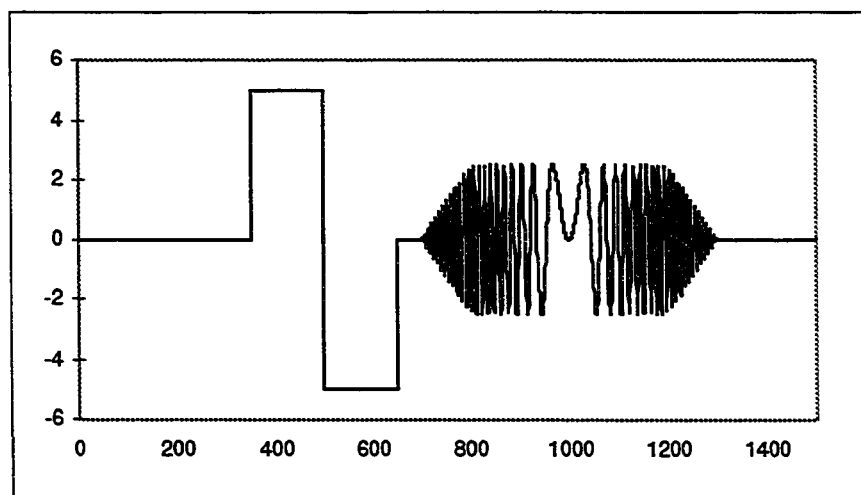
$$w(n) = \exp\left(\frac{j\pi n^2}{N}\right) \quad n = 0, \dots, N-1 \quad (2.6)$$

where n is the time index, N is the total number of samples in the wabulation signal, and j is the square root of -1 . The real and imaginary components of this signal are transmitted alternatively during even and odd frames, respectively. The real and imaginary components are also transmitted as positive and negative versions. Fig 2.2 shows the real and imaginary components of the complex wabulation function. Other existing GCRs include the frequency varying sinusoidal high energy U.S. standard reference signal [5, 19] shown in Fig. 2.3, and the randomly shaped Korean GCR [6] transmitted as positive and negative versions, alternatively (Fig. 2.4).

To design a GCR signal, certain points, such as the geographical or weather conditions, must be taken into consideration. Some of the proposed GCR signals are designed to suit some channel characteristics more than others due to features they have. In order to incorporate other channel features in a GCR, Lee, et al [11] proposed a reference signal modification system that modifies the GCR signal before transmitting it through the ghosting channel. The objective is to increase the rate of convergence of the Least Mean Square (LMS) algorithm used for channel identification and deghosting equalizer setting. According to the study presented by Lee, et al [11], the rate of



(a) Real component



(a) Imaginary component

Fig 2.2: The real and imaginary components of the complex wabulation signal [3].

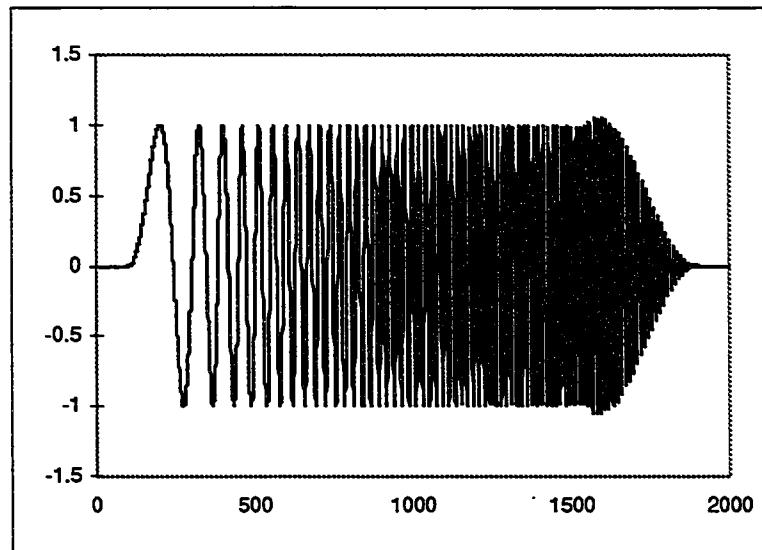
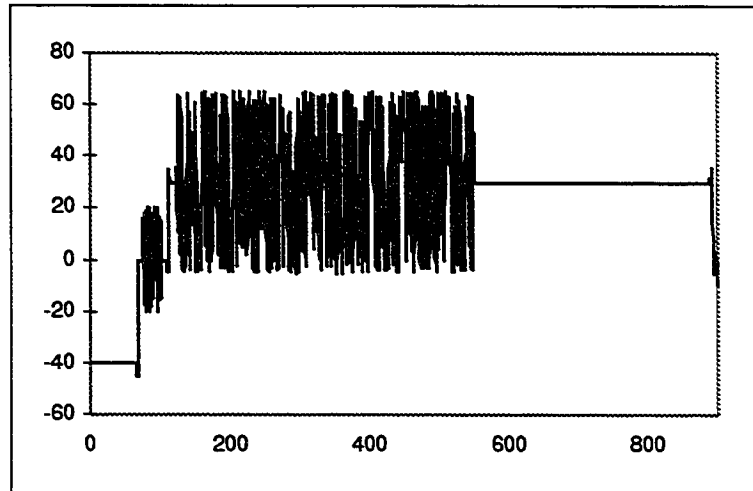
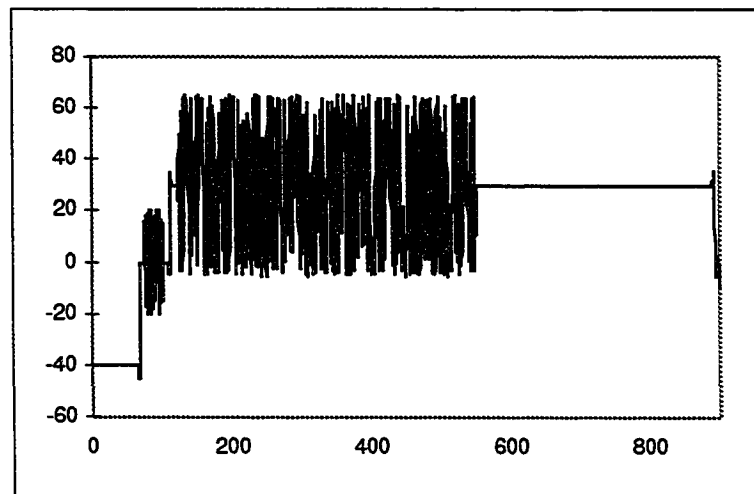


Figure 2.3: The standard high energy U.S GCR. [4, 5]



(a) Positive version



(b) Negative version

Fig 2.4: Positive and negative versions of the Korean GCR [6]

convergence of the LMS algorithm increases if the eigenvalues of the correlation matrix of the input signal are as close to each other as possible. This means that if the eigenvalues of the correlation matrix are made all equal, then this is the most effective GCR that can be used from the viewpoint of fast LMS convergence [11]. Fig. 2.5 shows a block diagram of the proposed GCR modification algorithm.

All GCR signals discussed so far try to determine the linear behavior of the ghosting channel. Sometimes, knowing the non-linear behavior of certain channels is important because these non-linearities affect the color contents of a video signal. To reveal the non-linear characteristics, Fiallos, et al [12] proposed the insertion of either a modulated or an unmodulated staircase signal in the GCR. The modified GCR provides information to the receiver for detecting any non-linear behavior in the ghosting channel. This modified GCR proposed by Fiallos, et al [12] is shown in Fig 2.6.

Wang [13] stated the requirements needed for getting a good GCR signal by looking at the problem from the viewpoint of random signal processing. He stated that GCR signals should have a flat spectrum, and a zero auto-correlation function at lags other than zero. The signal energy should be also as high as possible, and it should have an arbitrarily long length. The unit impulse is the only real-valued GCR signals that satisfies the first two criteria while failing to satisfy the condition of high energy or the long length [13]. A modification to this signal is the GCR of the Japanese Broadcasting Technology Association (BTA GCR), which has more power but it is seen to be sensitive to noise [13]. Another signal that satisfies the requirements to some extent is the Pseudo-

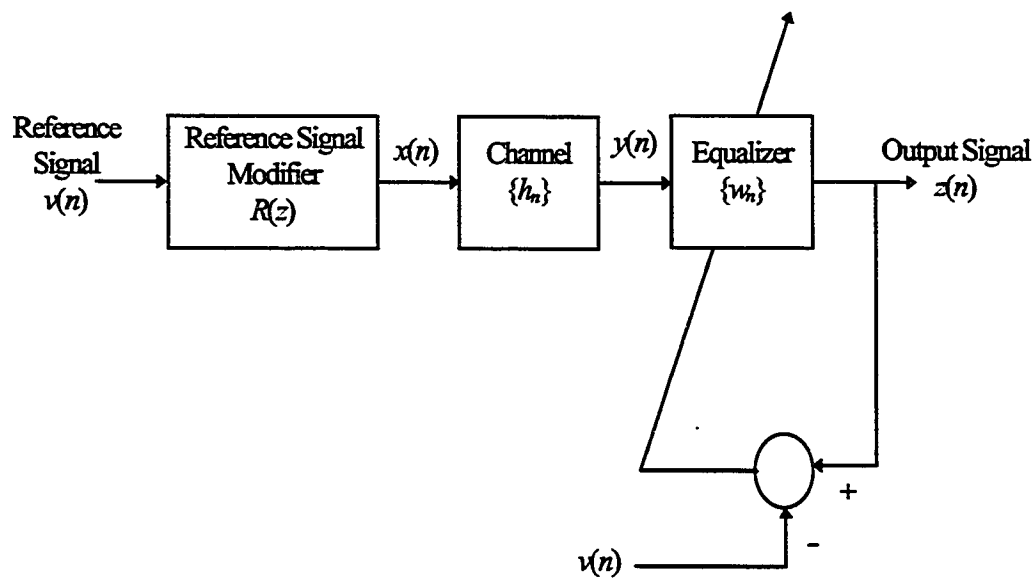


Fig 2.5: Equalization system using the reference signal modifier [11]

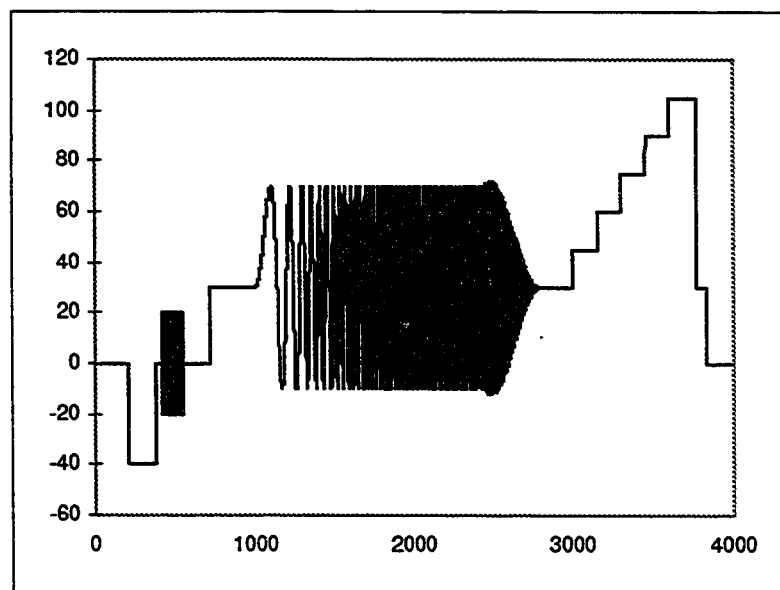


Figure 2.6: The staircase modified GCR for non-linear channel behavior detection [12]

Random sequence. The major drawback of this sequence is that it is hard to generate a pseudo random sequence with a completely flat spectrum [13]. To satisfy all the above requirements, reference [13] suggested the use of a Complex-Valued Ghost Canceling Reference (CVGCR). The features of the CVGCR that make it superior over other non-complex GCRs are the completely flat frequency spectrum it has and the ability of selecting its length almost arbitrarily.

Although some of the GCRs proposed in the literature give very good deghosting results, the major problem with most of them is the difficulty encountered with their generation and use to deghost TV signals. The generation of these GCRs is required not only at the transmitter, but also at the receiver. Perfect synchronization between the received and regenerated signal at the receiver must also be achieved to ensure successful deghosting. Moreover, the amount of computations associated with the GCRs proposed in the literature is usually large.

Whenever the requirements given in [13] are satisfied by a GCR, fast deghosting can be achieved. Fast convergence is usually important if a technique is recursive, meaning that a current estimate to the ghost channel is found by using its previous estimated values. If, however, the deghosting system is non-recursive, then some of these requirements may not be needed.

In this thesis, a new GCR sequence is proposed. The new GCR has a shape close to a square wave. This GCR can be used to reveal the impulse response of the ghosted

TV channel non-recursively but iteratively, i.e. the previous estimate may be used to enhance the new estimate.

2.3 OTHER COMMUNICATION FIELDS RELATED TO GHOST CANCELING

In communication systems other than TV, problems similar to ghosting exist. Two of the fields experiencing similar effects as ghosts in TV broadcasting are communication in telephone systems and in acoustic halls. In telephone systems, the transmitted voice signals are sometimes reflected back to the transmitter causing echoes. Transmitting audio signals in a relatively large hall also causes similar effects as TV ghosts and telephone echoes, where the receiver receives multiple components due to reflections causing echoes to be heard at the receiver.

2.3.1 Echo Cancellation in Telephone Systems

Telephone systems suffer from echo caused mainly by signal reflections at the two hybrids that change the communication from four-wire to two-wire and back to four-wire transmission [13]. Hybrids may cause reflections due to mismatched impedances at their terminals. In telephone lines, there are two types of echoes, namely near echo which happens at the hybrid of the local subscriber end, and far echo which occurs at the hybrid located at the remote subscriber end [13]. In the case of long-distance calls, specially when the channel involves a satellite link, the delay associated with the far echo becomes very

large. The delay associated with such telephone links may reach time delays of more than a second. Fig. 2.7 shows the block diagram of the signal transmission in telephone systems. The figure also shows the locations where possible signal reflection may occur. Since 1966, the date of the first paper discussing the issue of echo canceling in telephone systems by Sondhi [15], very extensive research has been done on the subject [16], and [17]. Recently, two papers presented by Hamied, et al [14, 18] discussed the issue of using telephone echo cancellation and channel equalization systems with fast start-up. The method they described for telephone systems is the basis of the system suggested in this thesis. The technique is to send a specific training sequence of bipolar bits in the channel modeled by a transversal tap-delay line. From this training sequence, a system of linear equations is generated. The solution of this system is used to estimate the tap coefficients of the channel. From these tap coefficients, the gains of the equalizer taps which cancels the effect of echoes can then be easily found [18]. The part of the process regarding channel identification is achieved with minimal calculations, involving neither multiplications nor divisions, and minimal storage elements. The proposed binary training sequence in telephone systems can serve as a GCR in TV transmission. This reduces the complexity of ghost canceling substantially.

The problem of echo cancellation in telephone systems is not exactly similar to that in TV ghost canceling. The difference between the two is that in telephone echo canceling, the canceller which is located at the transmitter end has an access to the transmitted signal all the time, hence training can be made at any instant. However, in TV ghost cancellation, the ghost canceling system has an access to the transmitted signal only

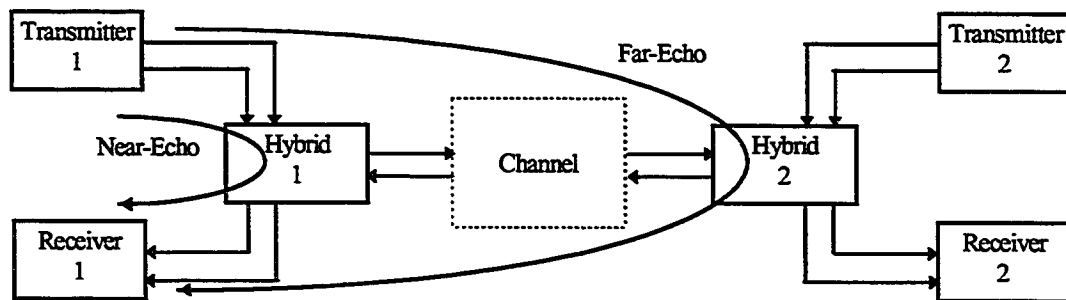


Figure 2.7: Signal transmission and reflection in telephone systems [14]

for a small portion of time which is during the transmission of the training sequence (GCR) only. The ghost canceling system depends on its channel estimation during transmission of the GCR to deghost the remaining part of the transmitted signal.

2.3.2 Echo Cancellation in Acoustic Halls

Due to the shape of large halls, usually the transmitted audio signal from a point in a hall reaches the receiver via many paths by reflecting over walls, ground, and ceiling [19]. Multiple reflections per path on the hall boundaries may also occur. Due to the very slow speed of sound relative to the speed of EM waves, relatively small halls may cause echoing. Since the human ear can distinguish two sounds that are delayed from each other by about 0.1 of a second or more, then any two paths that have a difference in length of 35 m or more cause clear echo. In Fig. 2.8, the multipath effect in acoustic halls is shown [19]. The figure shows the transmitter and the receiver (e.g. a speaker and a listener) in an acoustic hall where there are four different paths labeled (a), (b), (c), and (d). The two paths (a) and (b) have a single reflection while paths (c), and (d) have multiple reflections. It is clearly seen that different paths have different lengths, hence audio signals reach the receiver with different delays causing echo in large halls.

Echo in acoustic halls is much closer in nature to TV ghosts than echo in telephone systems. The difference between acoustic halls echo and TV ghosts is due to the high sensitivity of the human eyes compared to the ears. The major difference is the relatively long delay in echo cancellation that causes noticeable echo, compared to the small delay

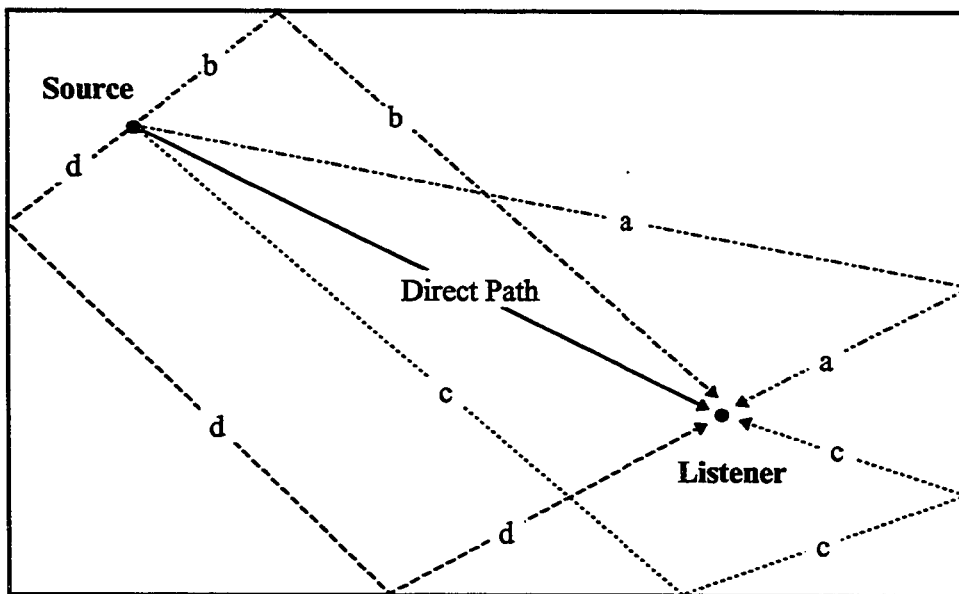


Figure 2.8: Multipath phenomena in acoustic halls [19]

required for the eye to sense TV ghosts. The required speed of computations in TV ghost canceling is also high while in acoustic halls echo canceling, the required speed is much slower. A difference between ghost canceling and acoustic halls echo canceling is that some information regarding the channel in acoustic halls may be available, as the reflection coefficient of the hall's walls, and some control on this channel may be possible while this is not available in TV ghosting channels.

2.4 SUMMARY

As seen in this chapter, significant research has been conducted on the field of ghost canceling in conventional analog TV. However, the systems proposed in the literature up to date require improvements. Improvements need to be done on all aspects of TV ghost canceling systems to assure optimality. Ideas from other communication fields similar to TV ghost canceling may also help in developing an optimum canceling system.

Chapter 3

TV GHOST CANCELING SYSTEMS

A designer of ghost canceling systems tries to reach the goal of designing a system that produces the best deghosting results with the fastest adaptation speed, the simplest and lowest amount of calculations, and the lowest amount of hardware components. Some of these requirements may contradict each other, so a compromise may be

necessary. In this chapter, the general requirement for successful TV ghost cancellation is discussed.

3.1 INTRODUCTION

As mentioned earlier, the improvements in TV systems are so rapid that the conventional TV will be eventually replaced by the newly proposed High Definition TV (HDTV) which has built-in ghost cancellation systems as a standard feature for outstanding performance. HDTV is expected to replace the exiting conventional TV with the advent of digital systems and their low cost implementation. However, due to the large installed base of conventional TV (broadcasting and receiving) systems, it is expected that HDTV will take a while to replace and dominate the TV market. As such, research and development on the enhancement of conventional TV, such as ghost canceling research, will continue experiencing a great support.

3.2 REQUIREMENTS FOR SUCCESSFUL GHOST CANCELING

The first generation of ghost canceling systems produced several years ago are considered to be unsuccessful. This can easily be proven by looking at their performance in the TV market which is seen to be very poor. Their deghosting performance, in general, is also very low compared to ghost canceling systems available today. Moreover, their size was very bulky to the point that some of them had the size of a VCR. A ghost

canceled system has to have several features for it to be successful. These features can be summarized in having an effective GCR signal to have the best deghosting quality, using an efficient adaptation algorithm for the fastest output and best tracking of channel variations, requiring the minimum amount of computations to perform ghost cancellation with the fastest speed, and using the minimum number of hardware components for it to have the lowest market price.

3.2.1 Effective GCR signals

For the ghost canceling system to produce acceptable deghosting results, it has to rely on an efficient source of information about the TV channel carrying the transmitted signal. The most optimum GCR is the one which can identify the channel most effectively. As mentioned in the literature [4, 5, 6, 12, 13], the most optimum GCR should have the following characteristics:

- The GCR should have a flat frequency spectrum in the band of the TV channel. This feature allows it to excite all the modes of the ghosting channel effectively. This condition can be satisfied by a GCR that sweeps the frequency range of the TV channel linearly as it is the case with sinusoidal frequency varying or randomly shaped signals as pseudo random GCRs.
- The eigenvalues of the auto-correlation matrix of the GCR should be equal. This feature is important in the case of recursive algorithms in order to achieve the highest

convergence speed. As the eigenvalues of the auto-correlation matrix become widely spread from each other, the convergence rate of the deghosting algorithm becomes slower. As the convergence of the algorithm becomes slower, it lacks the ability to follow fast variations in time varying channels, which is the case in many ghosting channels.

- The GCR's energy should be very high. It is important for the GCR to carry the largest amount of energy to be immune against additive noise as much as possible. If its energy is increased then its power also increases, hence the signal power to noise power ratio also increases. If a noisy GCR is used to deghost a TV signal, the system will not be able to deghost effectively compared to the use of a noise-free GCR. A very noisy GCR used for deghosting may also lead to corrupting the received signal instead of enhancing it.
- Finally, the time duration of the GCR should be maximized. As the time duration of the GCR increases, more information is given for the ghost canceling system to detect the channel characteristics, hence producing better channel estimates.

3.2.2 Efficient Adaptation

The ghost canceling system aims to deghost a ghosted TV signal as fast as possible. The importance of this feature is that a deghosting mechanism should be able to track any variation in the channel. If the deghosting system requires more time for

detecting the impulse response of the ghosting channel and adapting the deghosting equalizer than the time required for channel variation, then the deghosting system will not be able to deghost effectively. The reason is that the channel is changing with a speed faster than the speed of the deghosting process. Most of the available algorithms are fast enough to track time varying channels, but they differ in the speed of convergence. The requirements of an effective adaptation algorithm are also important for the purpose of reaching the final adaptation state with the minimum steady state error.

3.2.3 Computation Simplicity

Some deghosting algorithms may require a large number of computations to be performed for the deghosting process. As the amount of calculations increases, the adaptation to the ghosting channel becomes slower. Two sets of arithmetic operations are usually used in deghosting algorithms. They are the addition/subtraction and multiplication/division operations. It is well known that the floating point multiplication/division operations require roughly 10 times the number of clock cycles of those required to perform the addition/subtraction operations in a micro-processor environment or more. The reason for this long time required to perform multiplications/divisions is that these operations are usually performed in batch process, while the use of a carry look-ahead in additions/subtractions allows bit operations to be performed in parallel. So, as the number of multiplication/division operations is reduced, the speed of the deghosting process increases. On the other hand, the use of addition/subtraction operations is not that severe.

3.2.3 Hardware Simplicity

As the amount of computations increases, not only does the adaptation to the ghosting channel become slower, but also more hardware components are required. The multiplication/division operations, by nature, require more gates than the addition/subtraction operations. The memory elements required for performing multiplication/division operations is also higher than that required for addition/subtraction operations. As the number of components required by a ghost canceling algorithm increases, its complexity increases and hence its price also increases. Consequently, it loses its market competition.

It should be noted that the requirements for successful ghost canceling are very related to each other. A deghosting system that has a non-effective GCR, for example, usually has a slow adaptation algorithm and the required amount of computations and hardware components is large. To conclude, it is important to realize that the optimization of ghost canceling systems requires the optimization of each part of it.

3.3 GHOSTING CHANNEL TRANSFER FUNCTION

The form of the transfer function of a multipath (ghosting) channel in which there are n pre-ghosts and m post-ghosts along with a delayed main path component (the

total number of paths between the transmitter and receiver is $n + m + 1$ different paths) can roughly be said to have the following equation:

$$f(z) = \left(f_{-n} z^{T_{-n}} + \dots + f_{-1} z^{T_{-1}} + f_0 + f_1 z^{-T_1} + \dots + f_m z^{-T_m} \right) z^{-T_d} \quad (3.1)$$

where $f_{-n} \dots f_{-1}$ are the relative strengths of the pre-ghost components with corresponding advances of $T_{-n} \dots T_{-1}$, $f_1 \dots f_m$ are the relative strengths of the post-ghost components with corresponding delays of $T_1 \dots T_m$, and T_d is the overall delay of the whole channel which corresponds to the delay of the main path component that has a relative strength of f_0 (the strength of the main path f_0 is greater than all other component strengths $f_{-n} \dots f_m$).

In most practical TV channels, the pre-ghosts, if they exist, are characterized by having a very limited number, short advances, and are weak relative to that of the main path component. For these reasons, in most channels, the pre-ghosts may be safely ignored [8]. The post-ghosts, however, have strengths that are relatively high, their number may be large, and their time delays can reach several 10's of microseconds.

An exhaustive search in the literature to find some practical ghosting channel models revealed very few ones. Major difficulties are faced when using these proposed channels in the simulation of the proposed algorithm because of many reasons. Some of these channel models are very simple to use for the evaluation of the proposed system

because they contain a weak single ghost. Some other channels have several ghosts but they have very small delays such that it is hard to distinguish them from the original image, or the ghosts are very weak so they do not appear in the ghosted image at all. Some channels found in the literature are used in the simulation of the proposed algorithm along with some developed channels that are selected to show other features of the algorithm. Some channels used in the simulation of this thesis are deduced from the measurements done on real TV images.

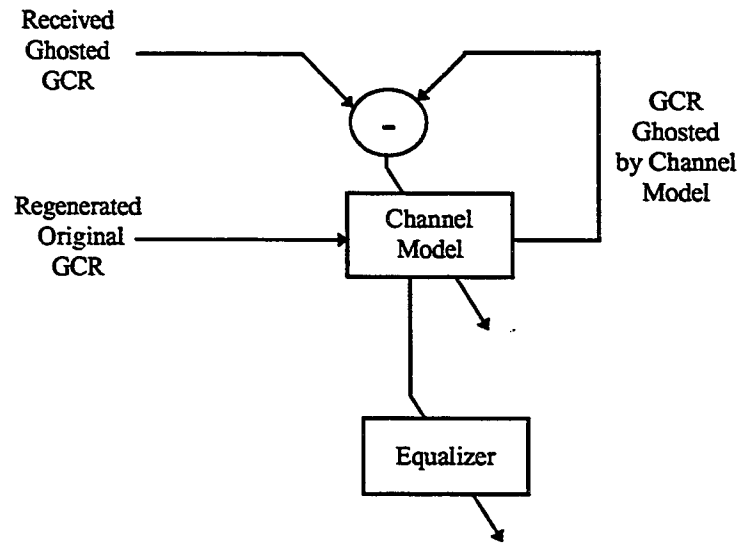
3.4 IDENTIFICATION OF THE GHOSTING CHANNEL TRANSFER FUNCTION

To start with, it is important to mention that all GCRs are inserted in the TV signal for the intention of channel identification. Therefore, all ghost canceling systems identify the ghosting channel impulse response using the received ghosted GCR. Once the channel is identified, equalization can be performed by adjusting the equalizer taps according to a certain algorithm such that the equalizer does the inverse process performed by the ghosting channel. However, there are two types of deghosting strategies [8]. The first type of deghosting algorithms is the direct deghosting method in which the channel is first identified using the received GCR. At this point of the process, the channel impulse response is estimated at the receiver. After the channel identification, the equalizer taps are optimally adjusted according to the identified channel transfer function using a certain algorithm [8]. The use of the GCR in this algorithms is in the process of channel identification only. Once the channel is identified, the GCR has no role in finding the

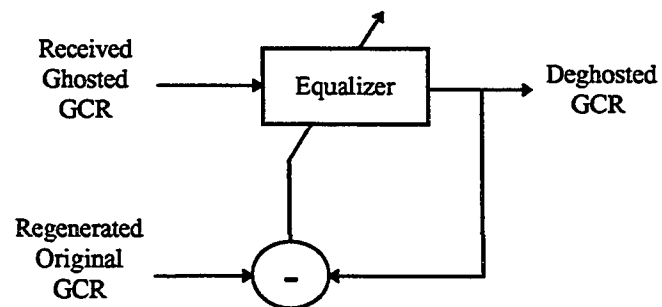
equalizer taps to be selected. Simply, the received GCR is used in the process of channel identification such that to minimize the difference between the received ghosted GCR and the output of the estimated channel when it is fed with the original GCR. Fig 3.1 (a) shows the process of deghosting using this algorithm.

The second type of deghosting algorithms is the indirect method, where the channel identification is not directly performed, but it is embedded in the process. In this type of deghosting algorithms, the GCR is used to identify the optimum equalizer taps that deghost the received ghosted TV signal in a single step. Here, the GCR is used for the equalizer identification such that it minimizes the difference between the original GCR and the output of the equalizer, in the least square sense, when it is fed with the received ghosted GCR [8]. The block diagram of the process of indirect ghost canceling is shown in Fig. 3.1 (b).

In certain cases, the indirect deghosting algorithm is preferred because it usually requires less number of calculations for each iteration in the adaptation process compared to the first method (if the same adaptation algorithm is used in both methods) and usually does not require matrix inversion as it is usually the case with the direct method [8]. However, the adaptation process of the indirect method usually requires a much larger number of iterations than the adaptation of the direct method. If the direct method is applied on an algorithm requiring simple calculations for the channel identification, then only few simple calculations are made to check if readjustments are necessary. However,



(a) The direct deghosting method



(b) the indirect deghosting method

Fig 3.1: The direct and indirect deghosting systems

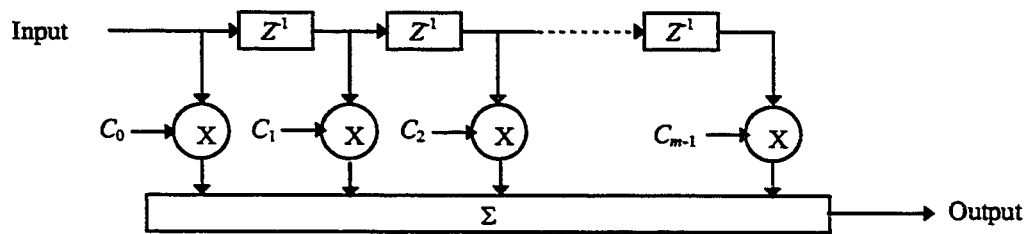
if the indirect method is used, the process of determining whether readjustments are required or not is a much more involved process.

Whether the first (direct) or the second (indirect) methods are applied in a ghost canceling system, an equalizer is needed for the purpose of reversing the process of ghosting introduced by the ghosting channel. Two different types of equalizers may be used for this purpose, the FIR and the IIR equalizers. Fig 3.2 (a) shows the structure of the FIR equalizer, and Fig 3.2 (b) shows the construction of the IIF filter. Each has its own features and characteristics which make it preferred over the other in different ghosting systems. To summarize, the IIR can remove ghosts more effectively than the FIR even if it has fewer taps. An advantage of the FIR is its unconditional stability while the IIR may become unstable for some settings. This means that after each adaptation, the stability of the IIR has to be checked [9].

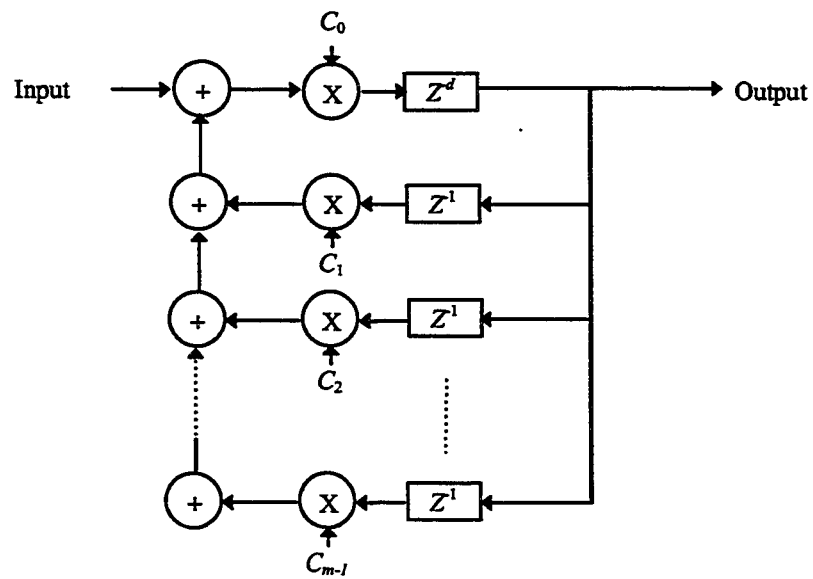
3.5 EQUALIZATION OF THE GHOSTING CHANNEL

The FIR is very widely used in TV deghosting, including the deghosting system proposed in this thesis, due to its simplicity. The general form of the impulse response of an FIR equalizer with m tap coefficients and $(m - 1)$ delay units is given by:

$$h(z) = c_0 + c_1 z^{-1} + \dots + c_{m-1} z^{-(m-1)} \quad (3.2)$$



(a) Transversal FIR filter.



(b) Transversal IIR filter.

Figure 3.2: Structures of the FIR and IIR transversal filters.

where c_0, c_1, \dots, c_{m-1} are the m tap gains of the equalizer. If an FIR filter with m taps is used for deghosting, then it can produce a ghost suppression (attenuating the undesired signal) which is usually proportional to the number of taps it contains. A relationship between the number of taps of the FIR equalizer m and the Desired to Undesired ratio (D/U) of the output to the D/U of the input [9] is given by:

$$m = \frac{\log\left(\sqrt{(D/U)_{\text{out}}}\right)}{\log\left(\sqrt{(D/U)_{\text{in}}}\right)} . \quad (3.3)$$

where D is the magnitude of the voltage of the desired signal (the unghosted signal), U is the magnitude of the undesired signal voltage (the ghost), and m is the number of taps of the equalizer. It is easily seen that, theoretically, an infinite number of taps is required to obtain a complete (infinite) undesired signal suppression. The situation of having an FIR equalizer with infinite number of taps is practically unrealizable. Needless to say that the design complexity of equalizers increases as the number of filter taps increases. From equation (3.3), it is clearly seen that the undesired signal suppression approaches zero (i.e. the output D/U is equal to the input D/U) as the level of the ghost approaches the level of the desired signal. This is one of the weaknesses of FIR filters. However, it rarely happens that the ghost signal reaches the same level as the main path signal.

3.6 SUMMARY

Successful ghost cancellation systems are characterized by having a very efficient GCR, using an effective adaptation algorithm and requiring a limited amount of hardware components for performing a limited number of computations. Ghost canceling systems follow one of two deghosting methods, i.e. the direct and indirect approaches. The direct deghosting approach identifies the ghosting channel impulse response using the received GCR first, then it designs an equalizer according to the estimated channel. The indirect approach adapts the equalizer taps directly using the received ghosted GCR without the need to explicitly identify the channel first. Two types of equalizer filters, the FIR and IIR, may be used. In most of the cases, the FIR is preferred due to its practical structure and ease of implementation, although it may require more taps.

Chapter 4

PROPOSED TV GHOST CANCELING SYSTEM

Previous developments proposed in the field of TV ghost canceling were presented in Chapter 2, and the characteristics required for developing efficient TV ghost canceling systems were discussed in Chapter 3. It is seen that some of the deghosting systems proposed in Chapter 2 satisfy some of the requirements needed for successful ghost canceling, such as having a flat frequency spectrum GCR with a zero auto-correlation

function for lags other than zero. However, it is clearly seen that some of the requirements outlined in Chapter 3 are not satisfied by all previous ghost canceling systems proposed in the literature. These requirements are considered the motive for having a ghost canceling system that uses simple calculations and requires a limited number of computations and components. This mandates the search for a class of GCR signals that can provide an effective deghosting scheme with a simple structure.

4.1 INTRODUCTION

Since the start of TV ghost cancellation, many algorithms have been proposed. Some algorithms are implemented due to their relatively practical structure, while others are not due to their complexity. The basic idea of the algorithm proposed in this thesis is presented in [14, 18] for telephone echo canceling. The proposed algorithm has many advantages over the existing ones. In this section the structure of the proposed ghost canceling system is described. Fig 4.1 shows the block diagram of the ghost canceling system proposed in this thesis. The system tuning parameters and their effect on the system performance are also discussed.

4.2 ESTIMATION OF THE TV CHANNEL USING THE PROPOSED GCR

As mentioned earlier in Chapter 2, a ghosting channel is usually represented by an IIR filter. Hence, an IIR filter is required for the deghosting process. However, in

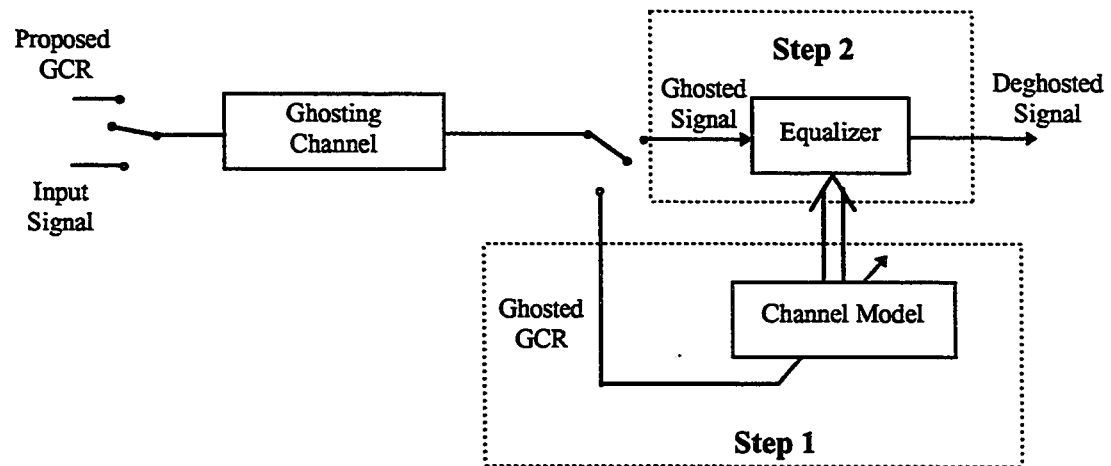


Figure 4.1: The two-step deghosting procedure.

most of the cases, an FIR filter is used. The proposed algorithm assumes a transversal FIR filter model with $(n+1)$ weighted taps for the ghosting channel, and proposes the use of a transversal tapped delay-line FIR deghosting equalizer with m taps. The choice of the parameter n should account for the most dispersive ghosting channel. The identification of a ghosting TV channel means finding its impulse response $f(z)$ given by:

$$f(z) = f_0 + f_1 z^{-1} + f_2 z^{-2} + \dots + f_n z^{-n} \quad (4.1)$$

or equivalently in vector form:

$$F^T = [f_0 \quad f_1 \quad f_2 \quad \dots \quad f_n]. \quad (4.2)$$

The equalizer length m is chosen to accommodate a wide variety of dispersive ghosting channels.

4.2.1 Channel Estimation of Noise-Free Channels

Initially, we assume that the channel is noise-free, i.e. the transmitted signal is corrupted by ghosts only. The discussion of noisy channels is presented later. If the transmitted GCR sequence is denoted a_0, a_1, a_2, \dots where the subscripts indicate the time index, then the received sequence is given by $v_s, v_{s+1}, v_{s+2}, \dots$ where s is an arbitrary delay such that $s \geq n$. For simplicity, s is considered here to have a value equal to n . The

transmitted and received sequences are related by the convolution between the transmitted sequence and the channel impulse response, i.e.:

$$v_k = \sum_{i=0}^n f_i a_{k-i}, \quad k = n, n+1, \dots \quad (4.3)$$

It is possible to use the above equation to form a system of $(n+1)$ linear equations in $(n+1)$ unknowns. This system of consecutive linear equations can be made linearly independent if the transmitted sequence is selected [18] according to the following relation:

$$a_k = (-1)^{\lfloor (k+n+2)/(n+1) \rfloor}, \quad k = 0, 1, \dots, (N+1)n+(N-1) \quad (4.4)$$

where $\lfloor x \rfloor$ denotes the largest integer less than or equal to x , and N represents the number of required averagings to reduce the effect of noise. In the case of noise-free channels, the shortest possible GCR that can be used has a length of $2n+1$ (i.e. $N = 1$). However, in the presence of noise, a longer GCR signal is needed. In general, the length of the GCR in terms of the channel dispersion and number of solutions is $(N+1)n+N$ samples. Table 4.1 shows the GCR for a channel of length $n+1$, number of solutions of N , and different sampling indexes. The waveform of the proposed GCR is plotted in Fig. 4.2. It is clearly seen from Table 4.1 and Fig. 4.2 that the shape of the proposed GCR is a bipolar square wave of $(N+1)$ positive and negative pulses. The system of linear

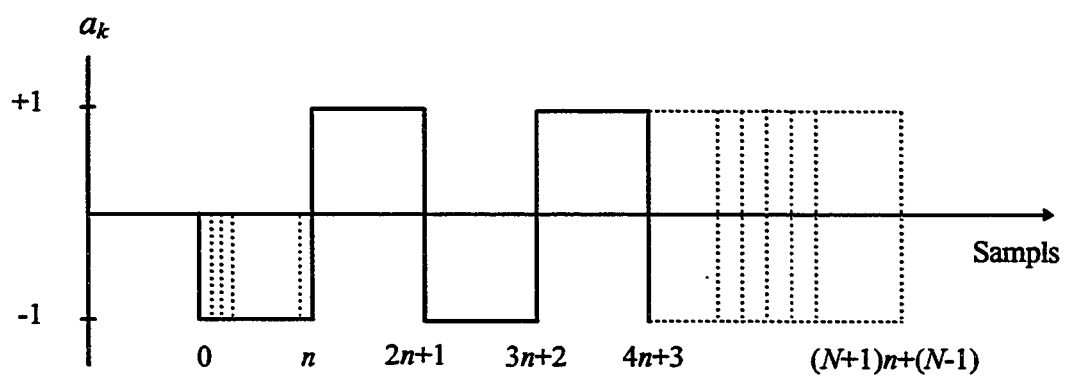


Fig. 4.2: The waveform samples of the proposed GCR signal.

Table 4.1: The value of the proposed GCR for different sampling indexes

Index		0	1	2	....	$n - 1$
GCR Value		-1	-1	-1	....	-1
Index	n	$n + 1$	$n + 2$	$n + 3$	....	$2n$
GCR Value	+1	+1	+1	+1	....	+1
Index	$2n + 1$	$2n + 2$	$2n + 3$	$2n + 4$	....	$3n + 1$
GCR Value	-1	-1	-1	-1	....	-1
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots
Index	$Nn+N-1$	$Nn+N$	$Nn+N+1$	$Nn+N+2$	....	$(N+1)n+(N-1)$
GCR Value	$(-1)^{(N+1)}$	$(-1)^{(N+1)}$	$(-1)^{(N+1)}$	$(-1)^{(N+1)}$	....	$(-1)^{(N+1)}$

equations obtained from the received sequence can be written as:

$$V_j = (-1)^j \Theta F, \quad j = 0, 1, 2, \dots \quad (4.5)$$

where

$$\Theta = \begin{bmatrix} +1 & -1 & -1 & -1 & \dots & -1 \\ +1 & +1 & -1 & -1 & \dots & -1 \\ +1 & +1 & +1 & -1 & \dots & -1 \\ +1 & +1 & +1 & +1 & \dots & -1 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ +1 & +1 & +1 & +1 & \dots & +1 \end{bmatrix}, \text{ and } V_j = \begin{bmatrix} v_{n+j(n+1)} \\ v_{n+j(n+1)+1} \\ \vdots \\ v_{2n+j(n+1)} \end{bmatrix}.$$

As mentioned earlier, the system of linear equations (4.5) is linearly independent since it is easily verified that Θ has a full rank of $(n+1)$ for any selection of the channel length $n+1$.

Hence, Θ is invertible with an inverse given by:

$$\Theta^{-1} = \begin{bmatrix} +0.5 & 0 & 0 & 0 & \dots & +0.5 \\ -0.5 & +0.5 & 0 & 0 & \dots & 0 \\ 0 & -0.5 & +0.5 & 0 & \dots & 0 \\ 0 & 0 & -0.5 & +0.5 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & +0.5 \end{bmatrix} \quad (4.6)$$

The j th solution set of the system of equations (4.5) to find the impulse response of the channel F is given by:

$$\begin{aligned}
 F &= (-1)^{-j} \Theta^{-1} V_j = (-1)^j \Theta^{-1} V_j, \quad j = 0, 1, 2, \dots \\
 &= (-1)^j \begin{bmatrix} +0.5 & 0 & 0 & 0 & \dots & +0.5 \\ -0.5 & +0.5 & 0 & 0 & \dots & 0 \\ 0 & -0.5 & +0.5 & 0 & \dots & 0 \\ 0 & 0 & -0.5 & +0.5 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & +0.5 \end{bmatrix} \begin{bmatrix} v_{n+j(n+1)} \\ v_{n+j(n+1)+1} \\ \vdots \\ v_{2n+j(n+1)} \end{bmatrix} \\
 &= \frac{(-1)^j}{2} \begin{bmatrix} v_{n+j(n+1)} + v_{2n+j(n+1)} \\ v_{n+j(n+1)+1} - v_{n+j(n+1)} \\ v_{n+j(n+1)+2} - v_{n+j(n+1)+1} \\ \vdots \\ v_{2n+j(n+1)} - v_{2n+j(n+1)-1} \end{bmatrix}
 \end{aligned} \tag{4.7}$$

or equivalently, the coefficients $f_0, f_1, f_2, \dots, f_n$ are given by:

$$\begin{aligned}
 f_0 &= \frac{(-1)^j}{2} [v_{n+j(n+1)} + v_{2n+j(n+1)}] \\
 f_i &= \frac{(-1)^j}{2} [v_{n+j(n+1)+i} - v_{n+j(n+1)+i-1}], \quad i = 1, 2, \dots, n.
 \end{aligned} \tag{4.8}$$

It is well known that other ghosting channel identification and deghosting algorithms require the reproduction of the original GCR at the receiver in order to compare it with the received GCR. The reproduction of the GCR requires an extra amount of circuitry at the receiver and needs perfect synchronization between the received and reproduced

GCRs. Unlike other ghosting channel identification methods, the solution achieved through equation (4.8) indicates that the generation of the GCR at the receiver is not required. This is an added desirable feature to the proposed GCR in the sense of receiver structure simplicity.

4.2.2 Channel Estimation for Noisy Channels

In the presence of additive noise with zero mean and variance σ_n^2 in the channel, the received sequence r_k is the sum of the noise-free ghosted sequence v_k given in equation (4.3) and the noise w_k at every time instant:

$$\begin{aligned} r_k &= v_k + w_k, & k = s, s+1, \dots \\ &= \sum_{i=0}^n f_i a_{k-i} + w_k, & k = s, s+1, \dots \end{aligned} \quad (4.9)$$

The received sequence becomes now a function of the noisy estimate of the channel \hat{F} . So, equation (4.5) can be modified to be in terms of the noisy channel estimate \hat{F} instead of the noise-free channel estimate F as:

$$R_j = (-1)^j \ominus \hat{F}_j, \quad j = 0, 1, 2, \dots \quad (4.10)$$

where

$$R_j = \begin{bmatrix} r_{n+j(n+1)} \\ r_{n+j(n+1)+1} \\ \vdots \\ r_{2n+j(n+1)} \end{bmatrix}, \quad \text{and} \quad \hat{F}_j = \begin{bmatrix} \hat{f}_{0,j} \\ \hat{f}_{1,j} \\ \vdots \\ \hat{f}_{n,j} \end{bmatrix}.$$

Doing a similar procedure to the case of noise-free channels, the j th set of solutions (sets of solutions are different now due to the presence of noise) to this modified system of equations is given by:

$$\begin{aligned} \hat{f}_{0,j} &= \frac{(-1)^j}{2} [r_{n+j(n+1)} + r_{2n+j(n+1)}] \\ \hat{f}_{i,j} &= \frac{(-1)^j}{2} [r_{n+j(n+1)+i} - r_{n+j(n+1)+i-1}], \quad i = 1, 2, \dots, n. \end{aligned} \quad (4.11)$$

where $\hat{f}_{i,j}$ is the j th estimate of the i th component of the channel impulse response, and r_i is the i th received noisy sample. Each set of solutions represents an estimate to the impulse response of the channel using different portions of the GCR. To get a better estimate, we can average N consecutive noisy estimates. The averaged estimate is given by:

$$\begin{aligned}
\hat{f}_0 &= \frac{1}{2N} \sum_{j=0}^{N-1} (-1)^j [r_{n+j(n+1)} + r_{2n+j(n+1)}] \\
\hat{f}_i &= \frac{1}{2N} \sum_{j=0}^{N-1} (-1)^j [r_{n+j(n+1)+i} - r_{n+j(n+1)+i-1}], \quad i = 1, 2, \dots, n.
\end{aligned} \tag{4.12}$$

As, the number of solutions N increases, the estimated channel impulse response improves. In order to see how much improvement this averaging has made, we can compare the mean square error of a single estimate given by:

$$E[(\hat{f}_{i,j} - f_i)^2] = \frac{\sigma_n^2}{2} \quad i = 1, 2, \dots, n. \tag{4.13}$$

with the mean square error of the average estimate which is:

$$\begin{aligned}
E[(\hat{f}_i - f_i)^2] &= \frac{1}{N} \left\{ E[(\hat{f}_{i,j} - f_i)^2] \right\} \\
&= \frac{1}{N} \left\{ \frac{\sigma_n^2}{2} \right\} = \frac{\sigma_n^2}{2N}.
\end{aligned} \tag{4.14}$$

Clearly, the averaged estimate produces an error that is smaller by a factor of the number of solutions N used in the averaging. Hence, increasing the GCR length tends to enhance the channel estimation process. There is, however, some limitation on the number of solutions N mandated by the length of the GCR signal in one frame. On the other hand, longer GCRs can be obtained by augmenting individual GCR signals from consecutive frames.

To study the complexity of this technique, we need to consider the number of operations and the amount of storage elements needed. By a proper selection of N to be a power of 2, the division by $2N$ in the set of equations (4.12) can be performed by right bit shifting using a shift register instead of dividing. By doing this, the technique requires neither multiplication nor division for the step of channel identification. The channel identification requires only $(n+1)N$ addition/subtraction operations and only $2(n+1)$ storage elements are needed.

4.3 THE DEGHOSTING EQUALIZER DESIGN

Once the impulse response of the TV channel is estimated, the second step in the deghosting process, as seen in Fig. 4.1, is the design of the deghosting equalizer. The proposed algorithm assumes a transversal tapped delay line model for the deghosting equalizer. The optimum transversal delay line equalizer taps C_{opt} are the set of taps that best remove the effect of that particular ghosting channel that was estimated in the channel estimation step. The set of equalizer coefficients can be obtained [20] by:

$$C_{opt} = A^{-1}b \quad (4.15)$$

where

$$C_{opt}^T = [c_0 \ c_1 \ \dots \ c_{m-1}],$$

$$b^T = [0 \ \dots \ 0 \ f_n \ f_{n-1} \ \dots \ f_1 \ f_0 \ 0 \ \dots \ 0]$$

The number of proceeding zeroes in b is equal to $(h - n)$ where h represents the overall delay of the channel and vector b has a dimension m . The matrix A is an $(m \times m)$ square matrix having the elements α_{ij} given by:

$$\alpha_{ij} = \begin{cases} x_{|i-j|} + \sigma_n^2 \delta_{ij} & |i - j| \leq n \\ 0 & \text{elsewhere} \end{cases} \quad (4.16)$$

where

$$x_i = \sum_{j=0}^{n-i} f_j f_{j+i}$$

and δ_{ij} is the Kronecker delta function. Equation (4.15) gives the matrix A the following structure:

$$A = \begin{bmatrix} \alpha_0 & \dots & \alpha_n & 0 & \dots & 0 \\ \vdots & \alpha_0 & \dots & \alpha_n & \dots & 0 \\ \alpha_n & \vdots & \alpha_0 & \dots & \dots & 0 \\ 0 & \alpha_n & \vdots & \alpha_0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & 0 & \dots & \alpha_0 \end{bmatrix} \quad (4.17)$$

where $\alpha_{|i-j|} = \alpha_{i-j} = \alpha_{j-i}$. To find the optimum equalizer tap coefficients, the matrix A has to be inverted. The inversion of a matrix is usually a very time-consuming process. It also requires many multiplication and division operations along with a huge number of additions and subtractions (the inversion complexity and by consequence the number of multiplication/division operations increases as a function of the cube of the matrix dimension). The number of memory elements required in the direct matrix inversion is also high, especially with large matrix dimensions.

There are other inversion methods that lower the requirements needed for the inversion of the matrix A . Most of the matrix inversion algorithms available are iterative, such as the steepest descent and the Gauss-Seidel algorithms [5]. However, there are other more efficient algorithms for matrix inversion if the matrix to be inverted has some special structure. Since the elements of the major diagonal of matrix A and all parallel diagonals are equal, and since the matrix is symmetric around the its diagonal, then it is a Toeplitz structured matrix. Because of the special Toeplitz structure of the A matrix, it can be inverted using a very computationally efficient algorithm known as Levinson-Trench (refer to [5] for a thorough explanation of the Levinson-Trench algorithm for Toeplitz matrixes inversion). The Levinson-Trench inversion method takes advantage of the Toeplitz structure of matrix A having the elements α_{ij} given by equation (4.16). Once the matrix inversion is performed, direct multiplication by the vector b produces the equalizer tap coefficients.

According to [18], the requirements for determining the equalizer taps are $2m^2 - 3m$ multiplications, $2m - 3$ divisions, $2m^2 - 4m - 3$ additions, and $3m + 1$ storage elements. It is to be noted that the amount of calculations required for the Levinson-Trench matrix inversion algorithm is in the order of $2m^2$ multiplications and $2m^2$ additions, while for the direct matrix inversion, the number of required multiplications and additions is in the order of m^3 . It is to be observed that matrix A has only $(n+1)$ different elements to be computed, and that elements of A require a total number of $n+1-i$ multiplications and $n-i$ additions for calculating element a_i , then adding all the required computations and storage elements from the two steps of the process and the process of forming the matrix A , the number of required calculations is $2m^2 - 3m + \frac{1}{2}n^2 + \frac{3}{2}n + 1$ multiplications, $2m^2 - 4m - 3 + N(n + 1) + \frac{1}{2}n^2 + \frac{1}{2}n$ additions/subtractions, $2m + n - 2$ divisions, and $3m + 2n + 3$ storage elements. It is important to observe that matrix A has only n different elements to be computed, and that the calculation of the equalizer coefficients is performed only once after achieving the smoothed channel estimate using the averaged N solutions. In real-life application, such operations can be divided and performed along successive frames. In this case, the hardware structure simplicity is still maintained.

4.4 FEATURES OF THE PROPOSED TV GHOST CANCELING ALGORITHM

The proposed ghost canceling system greatly differs from previously proposed deghosting systems. First of all, its GCR is no longer sinusoidal or randomly shaped as

GCRs in the literature. The adaptation of this algorithm to detect the ghosting channel impulse response is also different. Moreover, the amount of its hardware requirements and the type of the required calculations is much less. Now that we have discussed the two-step process of deghosting consisting first of the step of channel identification and then the deghosting equalizer design, a discussion of the features and characteristics of the proposed deghosting algorithm is given. Some of the requirement for this algorithm to be optimized are also highlighted.

4.4.1 Spectrum of the Proposed GCR

From Equation (4.4), it is clear that the proposed GCR has the shape of a bipolar square wave with $(N+1)$ pulses as shown in Fig 4.2 (a). It is known that the spectrum of a square pulse is the sinc function. The spectrum of the proposed GCR can be found by taking the Fourier transform of the transmitted signal consisting of the sum of several square pulses. Since the transmitted signal has the following waveform:

$$V_{GCR} = \begin{cases} -1 & \text{for } 0 \leq t < (n+1)T \\ +1 & \text{for } (n+1)T \leq t < (2n+2)T \\ \vdots & \vdots \\ (-1)^{N+1} & \text{for } (Nn+N)T \leq t < ((N+1)n+N)T \end{cases} \quad (4.18)$$

where T is the sampling period, then the Fourier transform of the GCR is:

$$\begin{aligned}
\Im(V_{GCR}) = & -(n+1)T \cdot \text{sinc}((n+1)Tf) \cdot \exp(-j\pi(n+1)Tf) \\
& + (n+1)T \cdot \text{sinc}((n+1)Tf) \cdot \exp(-j\pi(n+1)Tf) \cdot \exp(-j2\pi(n+1)Tf) \\
& - (n+1)T \cdot \text{sinc}((n+1)Tf) \cdot \exp(-j\pi(n+1)Tf) \cdot \exp(-j2\pi 2(n+1)Tf) \\
& + \dots - \dots \\
& + (-1)^{N+1} (n+1)T \cdot \text{sinc}((n+1)Tf) \cdot \exp(-j\pi(n+1)Tf) \cdot \\
& \quad \exp(-j2\pi(N+1)(n+1)Tf) \tag{4.19}
\end{aligned}$$

$$\begin{aligned}
= & (n+1)T \cdot \text{sinc}((n+1)Tf) \cdot \exp(-j\pi(n+1)Tf) \cdot \left[-1 + \exp(-j2\pi(n+1)Tf) \right. \\
& \left. - \exp(-j2\pi 2(n+1)Tf) + \dots - \dots + (-1)^{N+1} \exp(-j2\pi(N+1)(n+1)Tf) \right]
\end{aligned}$$

The magnitude of the term in the square brackets is similar to a periodically repeated sinc function with the main lobes centered at frequencies $f = 1 / (2(n+1)T)$, $3 / (2(n+1)T)$, The term multiplied by the bracket is a sinc function centered at zero frequency and having zeroes at multiples of $1 / (n+1)T$. The complete spectrum is the product of this periodically repeated function and the sinc centered around zero frequency. The frequency spectrum of the GCR is shown in Fig. 4.3. It is seen from Fig 4.3 that the GCR has no DC component.

4.4.2 Selection of the GCR Length

As stated in the literature, the GCR is usually inserted in the base-band TV signal in the time allocated for vertical blanking. The total time allocated for blanking is about 60μs [13]. About 10μs of this time is devoted to the synchronization pulses, the color

bursts, and the front and back porches. Therefore, the remaining time of about $50\mu\text{s}$ is available for the ghost canceling system to use for GCR transmission. This gives a limitation on the possible length of the inserted GCR signal. Many considerations in selecting the length of the proposed GCR must be taken into account. In the proposed algorithm, the GCR has a length that is $N+1$ times of the channel dispersion $n+1$. As stated previously, the number of solutions N has to be selected as a power of 2 to avoid division in the channel identification stage. Noting that the duration of one sample in the proposed algorithm is equal to the duration of a TV pixel in the PAL color system, this implies that the sampling period is approximately equal to:

$$\begin{aligned}\text{One Sampling Period } T &= 1 / \{30 \text{ frames/second} * 525 \text{ lines/frame} * 500 \text{ pixels/line}\} \\ &= 0.127 \mu\text{s} / \text{pixel}.\end{aligned}$$

So, the number of GCR samples that can fit into the allocated time of $50\mu\text{s}$ is equal to 390 samples. Table 4.2 shows the preferred selections of the GCR length in order for it to fit in the available $50\mu\text{s}$, have the maximum possible length, and avoid division in the channel identification process.

From experimental measurements on real TV images, most of observed ghosts have delays of less than 40 sampling periods. Ghosts having delays more than 40 sampling periods are usually very weak so they can be safely ignored. The possible selections of GCR lengths given in Table 4.2 ranges from $30\mu\text{s}$ for $n = 25$ up to $50\mu\text{s}$

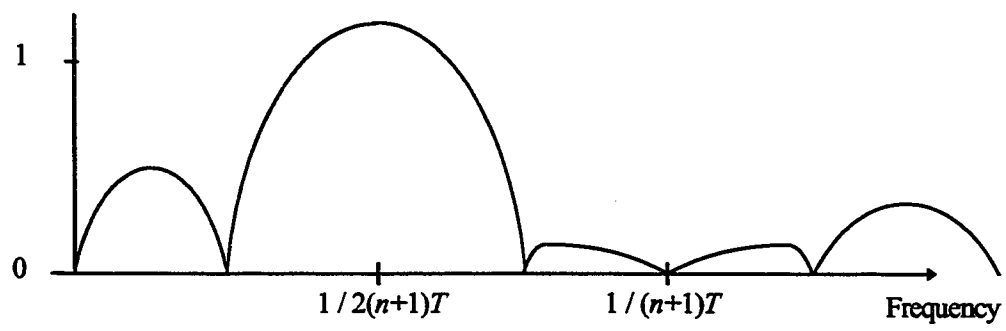


Fig 4.3: Frequency spectrum of the proposed GCR.

Table 4.2: Possible selection of the proposed GCR length

Delay units of ghost n (samples)	5	10	15	20	25	30	35	40
Max. Number of Solutions $N = \lfloor 390 / (n+1) \rfloor - 1$	64	34	23	17	14	11	9	8
Maximum Possible selection of N as power of 2	64	32	16	16	8	8	8	8
Number of samples $= (N+1) * (n+1)$	390	363	272	357	234	279	324	369
Duration of sample (μs) $= 50\mu\text{s} * [(N+1) * (n+1)] / 390$	50.0	46.5	34.8	45.7	30.0	34.6	41.5	47.3
% of $50\mu\text{s}$ used	100	93.1	69.7	91.5	60.0	71.5	83.0	94.6

for $n = 5$. For the maximum channel dispersion in the table which corresponds to $n = 40$, it is possible to select a GCR of length $47.3\mu\text{s}$ representing about 95% of the time allocated for GCR transmission. This percentage is relatively large since most of the time allocated for the GCR is used. In this case, a GCR producing 8 solutions can be inserted. It can be easily verified that for any selection of n , the minimum percentage of the whole time allocated for GCR transmission that can be used is 50%.

Since the minimum length of a GCR is approximately equal to twice the channel dispersion (i.e. when N is 1), then it is to be noted that only channels having a maximum dispersion of about 195 samples (corresponding to 195 TV pixels or $25\mu\text{s}$ between the main path and the most delayed ghost signal) or less can be estimated. This corresponds to a ghost that has a delay of more than one third of the width of the TV screen which is very rare. If the time allocated for the GCR transmission in a single frame can be used to transmit only a relatively small number of solutions, while a larger number is required to overcome large noise levels, then the time allocated for GCR transmission of more than one frame can be used where the solutions are concatenated.

4.4.3 Regeneration of the GCR at the Receiver

All proposed ghost canceling algorithms require the generation of the original GCR at the receiver end. Furthermore, perfect synchronization between the received and regenerated GCRs is vital. Whether the direct or indirect ghost canceling system tuning

methods is used, the receiver has to generate a copy of the original GCR and synchronize it with the received ghosted one. The importance of the regeneration of the GCR at the receiver comes from knowing that ghost canceling algorithms as the LMS, for example, make a comparison between each sample of the received and regenerated GCR. According to this comparison, correction is performed on the deghosting filter. We should observe that the proposed system does not require the generation of the GCR at the receiver due to the method of channel identification it uses. This provides a significant simplification in the construction of the ghost canceling system.

4.5 SUMMARY

The proposed ghost canceling algorithm has many attractive features that make it superior over other implemented or proposed systems in the literature. The major advantage of the proposed system over other ghost canceling systems is its implementation simplicity and low hardware requirements. Although this algorithm is considered as a direct ghost canceling system, which means that it requires a matrix inversion, the matrix to be inverted has the Toeplitz structure. This matrix structure can be inverted with minimal requirements using the Levinson-Trench algorithm for Toeplitz matrix inversion. The whole process requires a very limited number in the order of $2m^2 + Nn + \frac{1}{2}n^2$ addition/subtraction operations, and an amount of the order $2m^2 + \frac{1}{2}n^2$ multiplications. The required memory is in the order of $3m + 2n$ storage elements. Compared to other algorithms of the direct or indirect types, the required amount of

computations in this algorithm is much less than that required for other algorithms. The proceeding chapter provides a comprehensive evaluation of the proposed algorithm with a variety of ghosting channels used. Comparison with other existing schemes are also included.

Chapter 5

SIMULATION RESULTS AND PERFORMANCE EVALUATION

Every ghost canceling system has some parameters that must be adjusted for the system to reach its most optimum performance. In Chapter 4, such parameters in the proposed algorithm were discussed. It was seen in the previous chapter that the selection

of the number of solutions N , and the equalizer number of taps m change the system performance. To achieve the optimum settings for these parameters, the channel dispersion $n+1$ and the level of the additive noise must be taken into consideration.

5.1 PARAMETERS FOR MEASURING THE SYSTEM PERFORMANCE

There are some issues in the design of the proposed scheme that greatly affect its performance. Depending on the channel under consideration, some design parameters may have to be adjusted to achieve optimality in the sense of having the minimum Mean Square Error (MSE) between the original and deghosted GCR samples given by:

$$MSE = \frac{1}{(N+1)n+N} \sum_{k=0}^{(N+1)n+(N-1)} [(a_k - \hat{a}_k)^2], \quad (5.1)$$

where a_k and \hat{a}_k are the k th transmitted and deghosted GCR samples, respectively. Since the primary objective of this thesis is to find a good estimate of the ghosting channel, we introduce the channel coefficients error f_e which is defined as:

$$f_e = \frac{1}{n+1} \sum_{i=0}^n [(f_i - \hat{f}_i)^2], \quad (5.2)$$

where $n+1$ represents the channel dispersion given by the number of channel tap coefficients, and f_i and \hat{f}_i are the i th coefficients of the original and estimated channel impulse responses, respectively. This chapter presents the results of simulation in the quest of defining such optimal conditions. Moreover, comparison is made with the LMS [22], the simplest adaptation scheme available so far for the estimation of the ghosting channel with regard to performance (ability for deghosting) and complexity (the number of operations required).

Noise is added to the transmitted GCR after it is ghosted. The noise level added to the system is measured in terms of the Signal to Noise Ratio (SNR) defined in this simulation as the ratio of the signal power to the noise power. The proposed GCR is either a +1 or -1, so its power is unity, and since the power of the noise signal is σ_n^2 , then:

$$SNR = \frac{1}{\sigma_n^2} \quad (5.3)$$

The strategy followed in performing the simulation here is summarized as follows:

- The equalizer size is changed to see its effect on the quality of the deghosted output by observing the MSE of the output signal.
- A comparison with LMS results in the literature is made.

- The number of solutions N is varied and the error in the estimated channel coefficients f_e is observed for various additive noise levels.
- The effect of having a time-varying ghosting channel is studied on the performance of the channel identification process.

The simulations above are performed by computer programs written in C programming language according to the block diagram shown in Fig. 4.1 earlier. The first step in the deghosting process starts by ghosting the original GCR with the ghosting channel which is to be identified. Then, the ghosted GCR is used to estimate the channel impulse response coefficients. The second step is to find the optimum deghosting equalizer tap coefficients, and apply the ghosted signal to the equalizer to get the deghosted GCR at the equalizer output.

The delay unit in the simulation conducted here is the duration of one TV pixel. As mentioned previously, this gives the unit delay a time duration of about $0.127\mu\text{s}$. Four channels, shown in Fig. 5.1, are used in the simulation. The channel shown in Fig. 5.1 (a) is used in [2], where it has a single ghost having a strength of 30% of the main path. In [2], the delay between the ghost and the main path components is equal to 40 sampling periods, corresponding to about 4 samples here. So the channel used has a single ghost with relative strength of 30% and time delay of 4 sampling units. The second channel is shown in Fig. 5.1 (b). It has a main path component, a pre-ghost with a strength of 30%

of the main path and an advance of 4 units, and two post-ghosts with relative strengths of 40% and 30% of that of the main path with delays of 6 and 11 delay units, respectively. Two more small negative components exist at time indices 11 and 13.

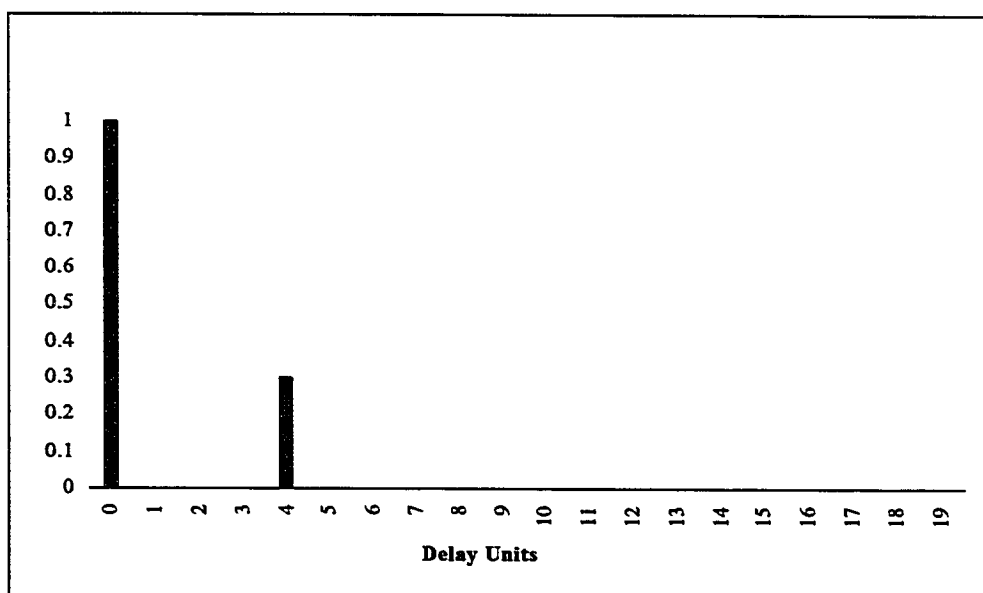
The channels shown in Fig. 5.1 (c) and Fig. 5.1 (d) each has two ghosts with relative strengths of 40% and 20% of the main path signal. However, the time indices of the ghosts in the channel of Fig. 5.1 (c) are 4 and 8, while the time indices of ghosts in the channel of Fig. 5.1 (d) are 6 and 10. These channels are used to study the performance of the proposed system in the presence of time variation in the ghosting channel.

5.2 PROPOSED GHOST CANCELING SYSTEM PARAMETER ADJUSTMENT

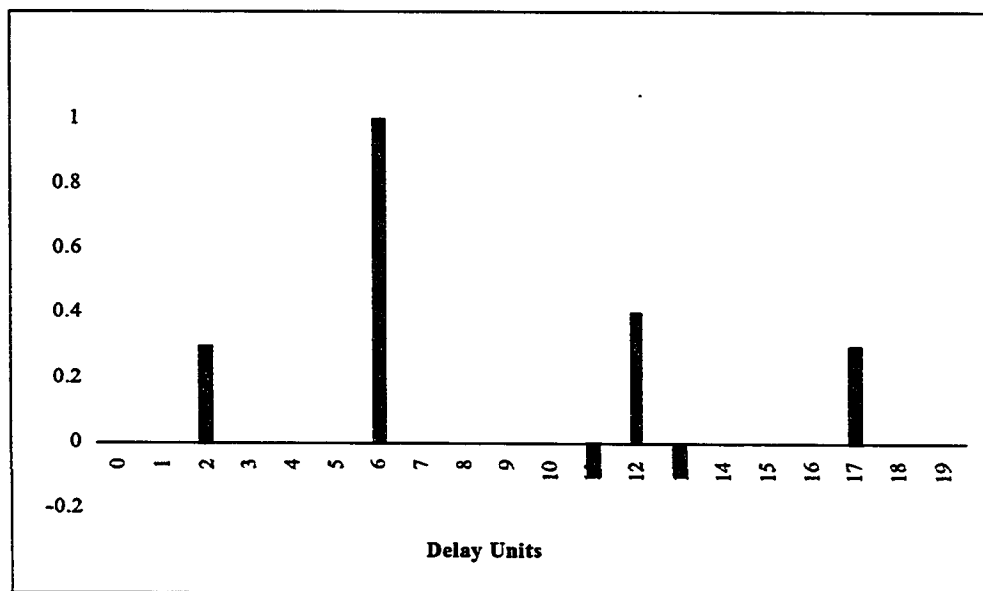
Different system parameters are studied in this section. The effect of varying these parameters is studied on the quality of the deghosted output. The optimum settings for these parameters are also studied.

5.2.1 Required Equalizer Size m

The discussion of the system performance starts with determining the required equalizer length before discussing the issue of channel identification requirements. Starting with a study of the required equalizer size is due to the necessary use of a much

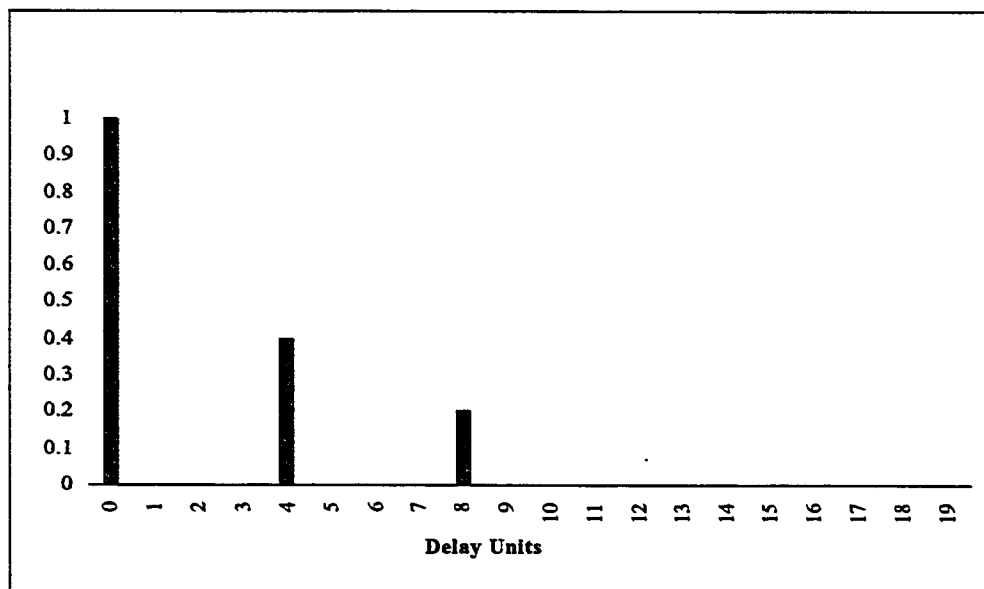


(a) Channel with a single ghost

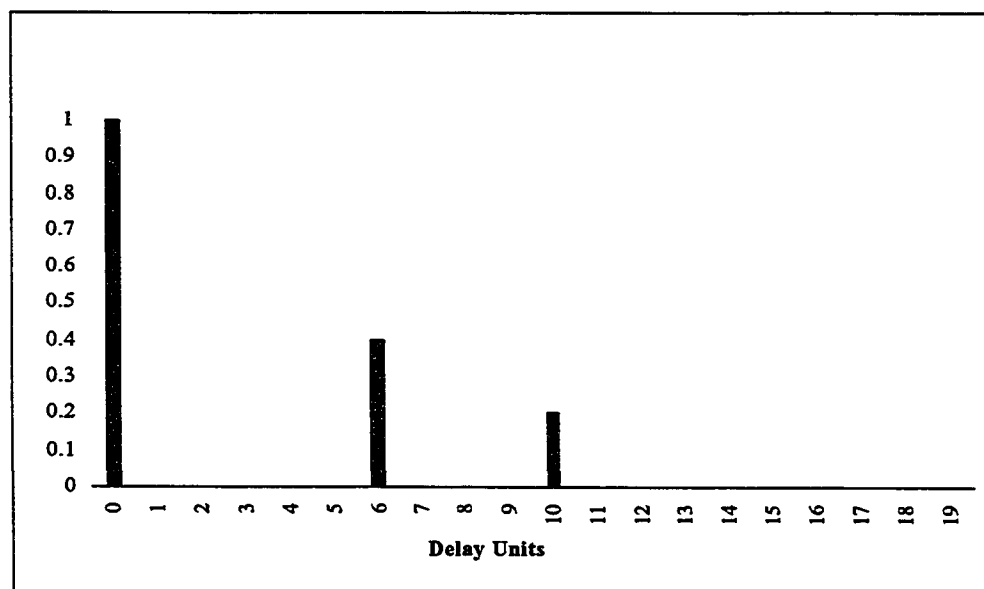


(b) Channel with one pre-ghost and two post-ghosts

Figure 5.1 (a) & (b): Impulse response of the channels used in simulation.
(1 Delay Unit = 0.13 μ seconds)



(c) Starting channel



(d) Ending channel

Figure 5.1 (c) & (d): Impulse response of the channels used in simulation.
(1 Delay Unit = 0.13 μ seconds)

simpler structure of the ghosting channel in this part, compared to the complexity of channels that are used in other simulation parts.

First, a noise-free version of the channel in Fig. 5.1 (a) is used in the simulation to evaluate the equalizer performance, with the delay between the single ghost and the main path component made variable in selected steps. The selected delay between the ghost and the main path component is first taken as 1 unit then as multiples of 5 delay units. The MSE between the transmitted and deghosted GCR signals is plotted versus the equalizer size in Fig. 5.2. The simplicity of this channel gives a good understanding of the effect of varying the equalizer length on the quality of the deghosted GCR. By observing the curves in Fig. 5.2, it can be seen that the MSE almost stays constant for certain equalizer size ranges as long as the size has not yet reached a value in which a new non-zero component is added to the equalizer. Since the equalizer tap-coefficients approach zero as the coefficient index increases, the drop of each step decreases as the equalizer size increases. In general, the curves tend to decrease as the equalizer length increases. Fig. 5.2 gives a very rough guide for the selection of the proper equalizer size to deghost a certain channel. The required equalizer size is selected as the value that gives a small MSE on the curve that has a ghost delay equal to the total channel dispersion of the channel in concern. It is obvious from the figure that the MSE in all curves have almost the same value for the same multiple of the channel dispersion $(n+1)$. This fact indicates that the non-zero equalizer taps in all deghosting filters are almost the same with the difference being the number of delay elements between these non zero taps. It is to be

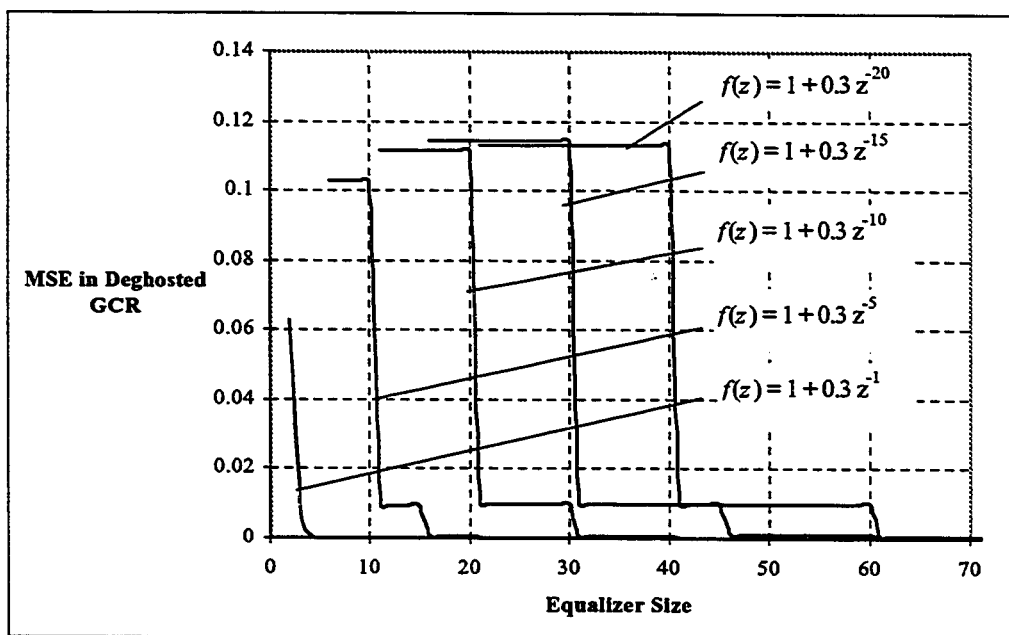


Figure 5.2: MSE of the deghosted GCR versus equalizer size for a channel with a single ghost and different ghost delays

noted that in the simulation of this part, the selected length of the channel impulse response in the simulation program (i.e. the number of channel coefficients to be estimated by the program) is selected to be equal to $n+1$, where n represents the number of delay units of the single ghost from the main path.

5.2.2 Effect of Varying the Number of Solutions N

Whether the number of solutions calculated by this algorithm is one or more, when the ghosting channel is noise-free (or the noise level is very small), all the channel estimates obtained from equation (4.11) by solving equation (4.10) are seen to be equal (or very close to each other). In the presence of additive noise, the solution sets obtained from equation (4.11) become different. The amount of deviation between different solutions depends on the noise level added to the transmitted GCR. To overcome the problem of noise, a number of solutions is averaged as in equation (4.12). As can be depicted that the mean square error of a single estimate given by equation (3.13) is N times larger than the mean square error of the average estimate given by equation (4.14). This indicates that, theoretically, as the number of solutions used in the averaging increases, the mean square error of the average estimate decreases by the same ratio.

The channel of Fig. 5.1 (b), which has a length of 18, is used to examine the effect of changing the number of solutions N on the channel coefficients error f_e for different noise levels. The effect of changing N is shown in Fig. 5.3 for different noise levels. The curves of this figure are associated with SNR values of 5, 10 and 20 dB's. It is clearly

seen that the general trend in the curves is that they decrease as N increases. For large SNRs, f_e becomes very small regardless of the number of solutions, implying that a very short GCR is required in the case of low noise levels. It is observed that regardless of the SNR, f_e drops very insignificantly as the number of solutions increases above $N = 5$. A practical selection for the number of averagings is in the range between 5 and 20, since the improvement when increasing N above 20 is negligible. To avoid division, the value of N should be selected as either 8 or 16.

5.3 COMPARISON WITH LMS GHOST CANCELING ALGORITHMS

The performance and requirements of the proposed algorithm are evaluated by comparing them with LMS ghost canceling algorithms proposed in [2] and [22]. The performance is studied by means of the convergence speed and the quality of the system output at the end of the adaptation process. For the same channel estimation error and hence the same deghosted signal quality, a comparison of the number of calculations required by the proposed and LMS algorithms is also presented.

5.3.1 Comparison Between Number of Calculations of Proposed and LMS Algorithms

The channel of Fig. 5.1 (a) is used again to compare the quantitative performance of the proposed deghosting algorithm with its binary GCR and the Stochastic Gradient

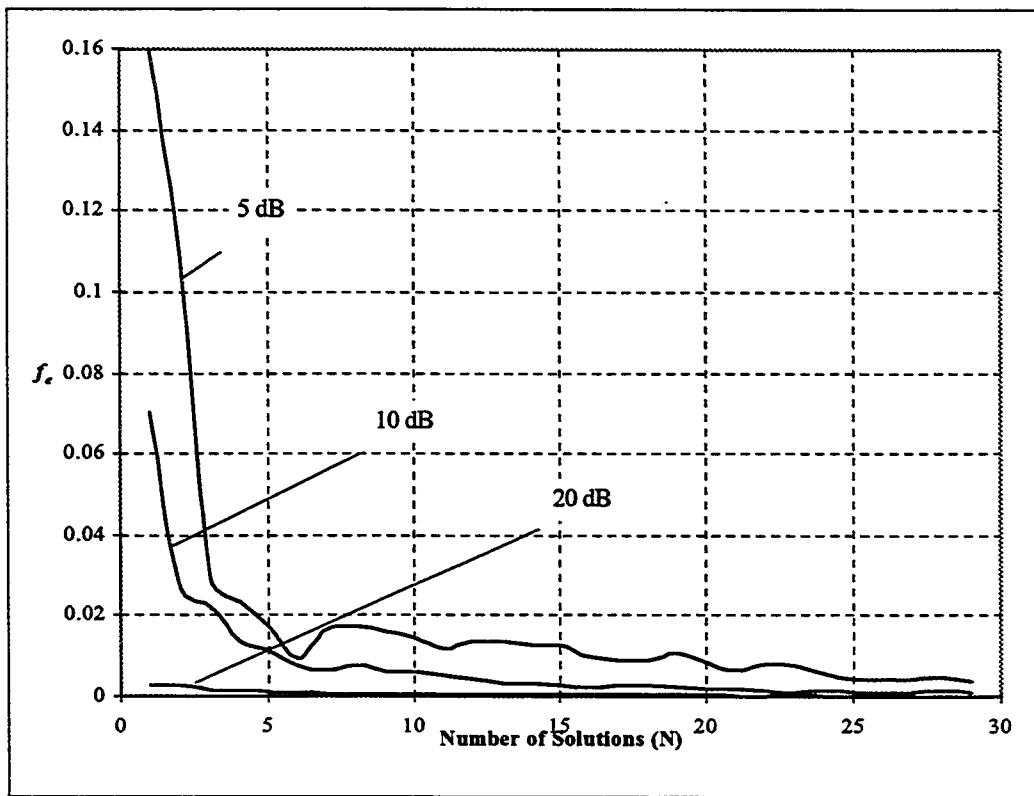


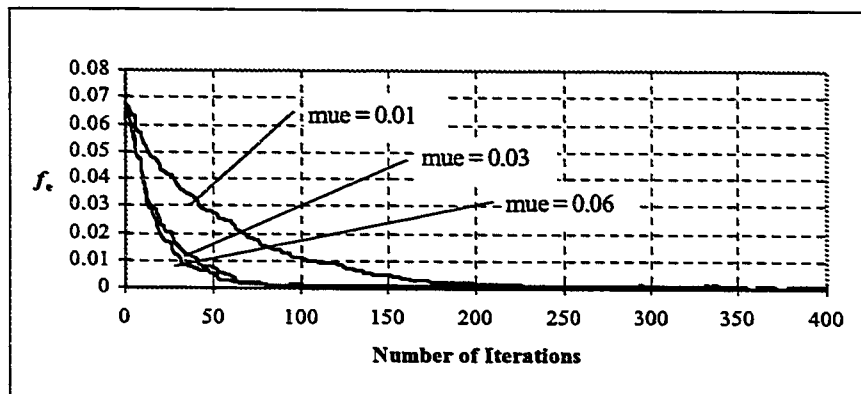
Figure 5.3: Channel coefficients error f_e versus the number of solutions N .
(Channel 5.1 (b) is used)

LMS (SGLMS) [2] which uses a frequency varying sinusoidal GCR. The SGLMS is seen to converge to the final equalizer tap values after roughly 7000 samples [2]. The GCR which has a time duration of about $50\mu\text{s}$ contains 3500 samples. This means that the required time for convergence is about $100\mu\text{s}$. This is equal to the time allocated for the GCR transmission in two frames. The convergence of the proposed technique requires from 5 to 10 solutions for different SNRs, hence requiring a time duration of $4\mu\text{s}$ to $7\mu\text{s}$ only. In the presence of low level noise, the required number of solutions for convergence is $N = 1$, which corresponds to a GCR having a duration of about $1.3\mu\text{s}$.

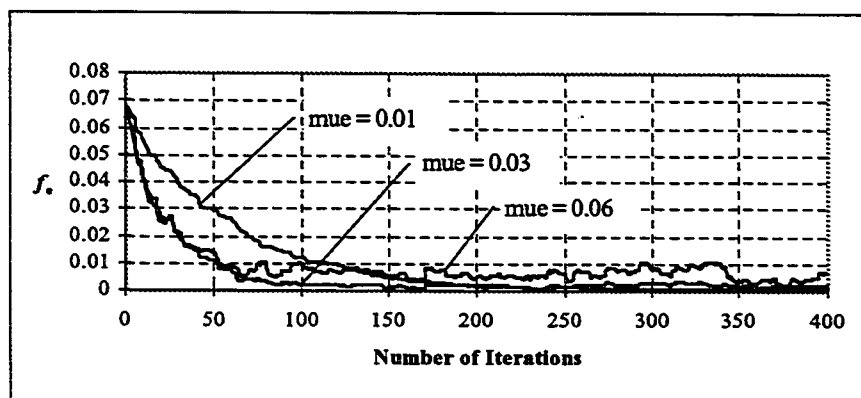
The size of the equalizer is equal to 13 taps in both algorithms. However, in the proposed algorithm, the adjustment is performed for all 13 equalizer taps, while in the SGLMS, only the 4 significant taps (non-zero taps at indices 0, 4, 8 and 12) are adjusted where 4 unit delays are placed between each two taps. Note that the solution provided in [2] is based on the prior knowledge of the ghost, which is impractical unless the channel is estimated first. Bearing in mind that the equalizer size m is 13, the channel length $n+1$ is 5, and the number of solutions N is 8 ($= 2^3$ to avoid division in the channel identification process by doing bit shifting instead), then the proposed algorithm requires 314 multiplications and 28 divisions compared to 63000 multiplications and no divisions in the SGLMS. The number of addition/subtraction operations required in the proposed algorithm is 333, compared to 56000 in the SGLMS. The required number of storage elements in the proposed algorithm is 50 compared to 14 in the SGLMS algorithm.

5.3.2 Comparison Between Convergence Speed of Proposed and LMS Algorithms

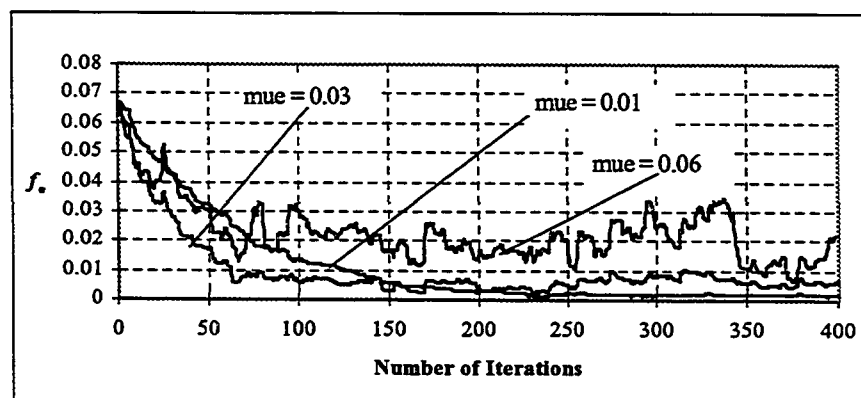
In order to compare the proposed channel estimator, the same channel of Fig. 5.1 (b) is considered again, using the simplified LMS technique [22]. Fig. 5.4 shows the convergence of the LMS for the same values of SNR considered above and with different step sizes. The GCR used for the LMS is a bipolar binary random sequence. Although the convergence of the LMS is fast with some SNRs and step sizes, in other cases, especially with small SNRs, it was either unable to converge fast enough or unable to converge at all. The comparison of the speed of convergence of the proposed system with that of the LMS is further illustrated in Tables 5.1 and 5.2. The comparison reveals that in many cases, the proposed system is faster in converging to the channel coefficients than the LMS for the same SNR. However, other cases give a relatively faster convergence rate in the LMS algorithm. Both tables show that for large SNRs, the convergence of the proposed system is very fast where it requires the minimum possible length of the GCR, which is twice the length of the channel. It should be observed that for every SNR, the proposed system is faster in convergence than at least one corresponding LMS adaptation curve for the same noise level. This indicates the importance of proper selection of the step size in the LMS algorithm for obtaining fast convergence. The selection of the proper step size for the LMS technique depends primarily on the received signal quality, i.e. the level of added noise and the ghosting channel dispersion (length). Since the received signal quality is not known *a priori* to the receiver, obtaining such a proper step



(a) SNR = 20 dB



(b) SNR = 10 dB



(c) SNR = 5 dB

Figure 5.4: Convergence of the LMS algorithm.
 (1 Iteration = 0.127 μ seconds)
 (Channel of Fig. 5.1 (b) is used)

Table 5.1: Delay units required for the proposed and the LMS algorithms to reach

$$f_e < 0.01$$

(Channel of Fig. 5.1 (b) is used)

	Step Size (μ)	SNR = 20 dB	SNR = 10 dB	SNR = 5 dB
Proposed algorithm	N/A	36	144	378
LMS	0.01	105	130	125
	0.03	40	50	330
	0.06	30	340	> 400

Table 5.2: Delay units required for the proposed and the LMS algorithms to reach
 $f_e < 0.02$

(Channel of Fig. 5.1 (b) is used)

	Step Size (μ)	SNR = 20 dB	SNR = 10 dB	SNR = 5 dB
Proposed algorithm	N/A	36	90	108
LMS	0.01	70	120	70
	0.03	25	30	45
	0.06	20	30	> 400

size is not easy in practice. This is not the case for the proposed system where no such parameter that determines the speed of convergence of the system exists.

5.4 EFFECT OF CHANNEL VARIATION ON THE CHANNEL IDENTIFICATION PROCESS

As it is well known, TV channels are usually time-varying channels. This means that the impulse response of the TV channel may change continuously with time. The speed of variation of TV channels is an important issue in studying the performance of ghost canceling systems. Since each ghost canceling system has a convergence speed, the convergence speed has to be faster than the variation in the ghosting channel to be able to track and deghost it. The speed of variation of ghosting channels differs according to its cause. If, for example, the cause of variation is a traveling vehicle like a plane or a car, then the variation may be sensed from one frame to the next. However, if the cause of variation in the ghosting channel is the change in the weather, for example, then the variation usually takes several seconds if not minutes to be observed. An effective ghost canceling system should be able to track channel variations of the fast type.

In indirect deghosting systems, tracking a time varying channel implies adjusting the deghosting equalizer taps continuously as the ghosting channel changes with time. However, in direct deghosting methods as the proposed algorithm, it is not necessary to readjust the deghosting equalizer tap coefficients for any small channel variation. The readjustment is performed after the current channel has changed from the one used in the

previous equalizer setting. Doing this reduces the number of required computations dramatically since the channel identification of this algorithm, for example, requires neither multiplication nor division.

The two channels shown in Fig. 5.1 (c) and Fig. 5.1 (d) are used in the time-varying channel simulation. Channel (c) represents the starting channel in the ghosting process while channel (d) represents the final one. The instantaneous channel used to ghost each frame is taken as the linear interpolation between each corresponding coefficient in channels (c) and (d) as in the formula:

$$f_i(\text{frame no.}) = f_i(c) + (\text{frame no.}) \frac{f_i(d) - f_i(c)}{\text{Total no. of frames}} \quad (5.4)$$

where $f_i(x)$ is the i th coefficient of the x th frame, $f_i(c)$ and $f_i(d)$ are the i th starting and ending coefficients, respectively, corresponding to the i th coefficient of channel (c) and (d), respectively.

Because of having a large number of channel estimates, one for each frame, a forgetting factor α is used in the process of channel estimation for time-varying channels. The forgetting factor is defined as the percentage of the new estimated channel used in forming the averaged channel estimate which is then used in forming the deghosting equalizer taps (i.e. for a forgetting factor of 1, the averaged estimated channel is completely defined as the new channel estimate, where the previous channel is completely

forgotten). The forgetting factor is used in forming the averaged channel estimate according to the formula:

$$\text{Average Channel Est.} = x \cdot \text{New Channel Est.} + (1-x) \cdot \text{Old Averaged Est.} \quad (5.5)$$

In Fig. 5.5 and 5.6, the MSE of the deghosted GCR is plotted for different forgetting factors and different speeds of variation (i.e. the number of frames to go from channel (c) to channel (d) increases for slower channel variations). In this part of the simulation, a relatively high noise level with an SNR equal to 5 dB is used. Fig. 5.5 corresponds to $N = 8$, while Fig. 5.6 corresponds to $N = 1$. In Fig. 5.5, it is seen that the MSE almost remains constant for most of the curves regardless of the forgetting factor x used. The reason is the relatively high quality of the channel estimate due to the use of 8 solutions to form each channel estimate. However, for very small forgetting factors, the MSE increases with the speed of the channel variation due to almost using the previous channel estimate completely in defining the averaged channel estimate. However, the old channel estimate defers greatly from the current channel especially for fast channel variations, hence causing the MSE to increase with the speed of channel variation.

The MSE of the deghosted GCR in Fig. 5.6 behaves differently when the number of solutions is reduced to $N = 1$. In this case, each new channel estimate is of low quality due to having a high noise level and using only one solution in the channel identification step. It is seen from the figure that for large values of x , the curves are also constant.

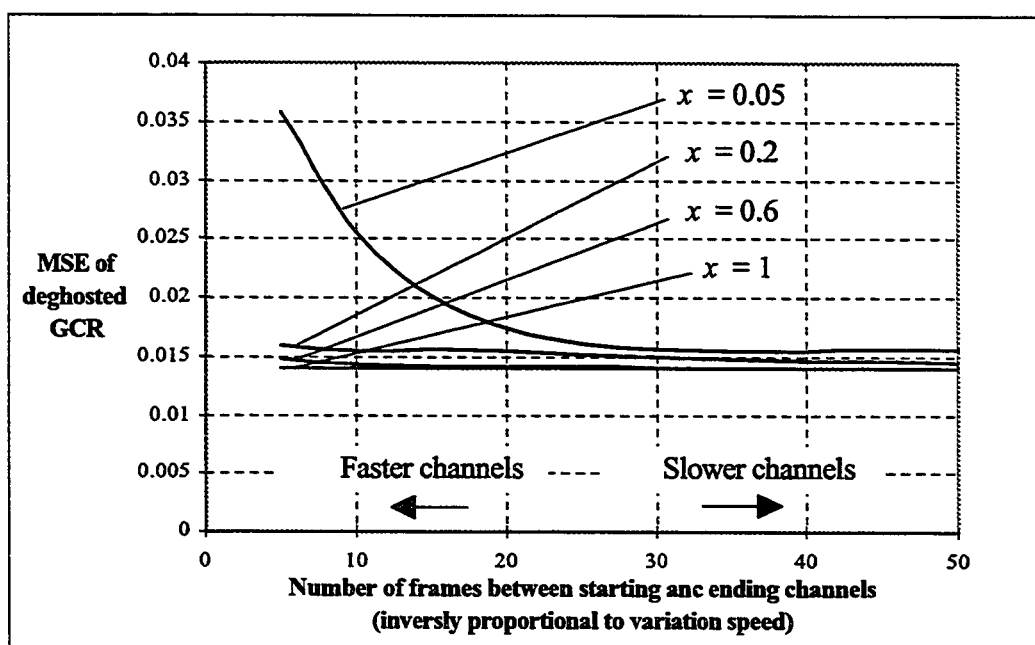


Figure 5.5 : Effect of channel variation speed on the MSE for different forgetting factors ($N = 8$) (channels of Fig. 5.1 (c) and Fig 5.1 (d) are used)

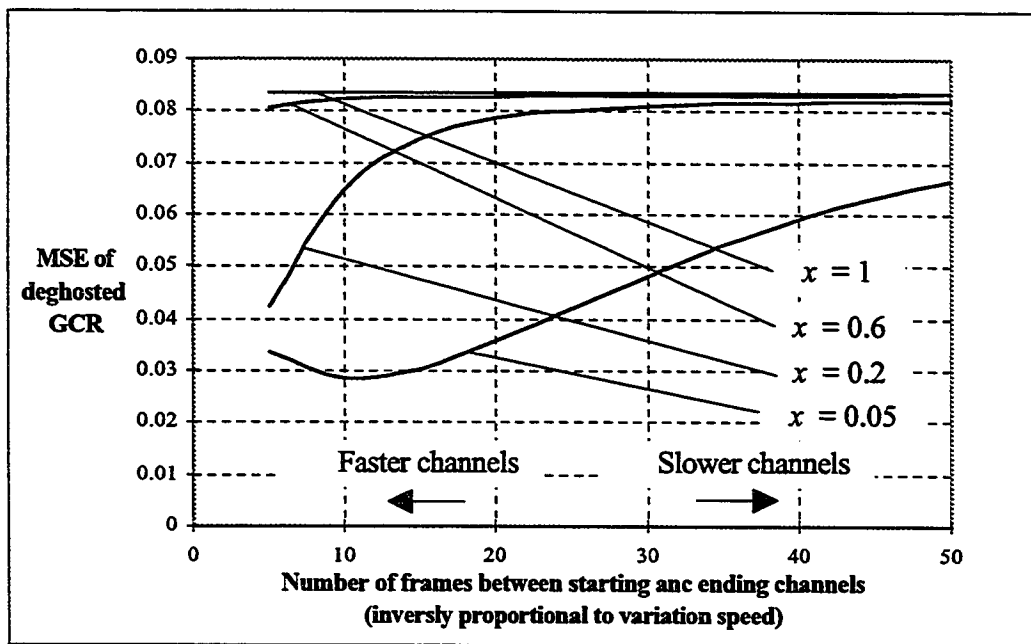


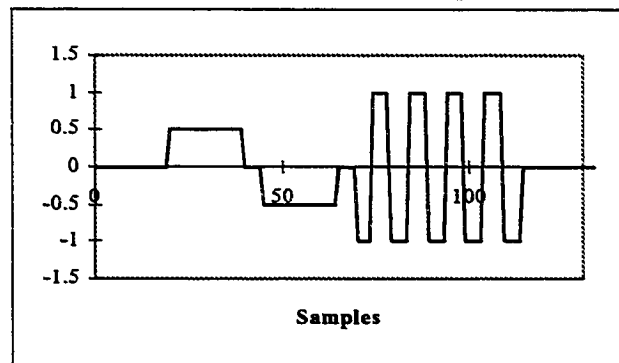
Figure 5.6 : Effect of channel variation speed on the MSE
for different forgetting factors ($N = 1$)
(channels of Fig. 5.1 (c) and Fig 5.1 (d) are used)

However, for smaller values of x , the MSE drops as the speed of channel variation increases to a certain limit. This can be justified by noticing that the use of a small x causes the error in the channel estimate to decrease where the error is averaged out by using previous channel estimates which are close to the current estimate for slowly varying channels. For very small x and very fast channels, the MSE starts to increase since the enhancement done by averaging the error when using previous channel estimates is opposed by the large difference between the new and the previously estimated channels.

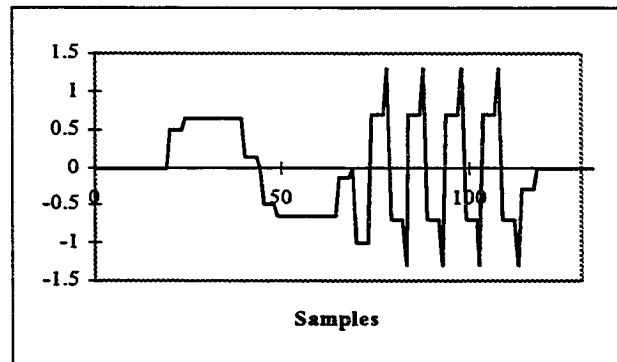
To summarize, if a forgetting factor is to be used in the process of time-varying channel identification, then it should be selected as a large value for large number of solutions N . However, if the channel dispersion is large causing a small number of solutions to be found in each frame, then a selection of a small forgetting factor is preferred to overcome the large error in the channel estimate.

5.5 APPLICATION OF THE PROPOSED ALGORITHM TO REAL IMAGES

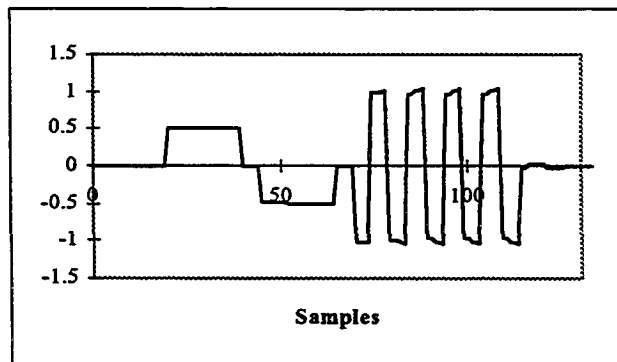
The proposed GCR signal is shown in Fig. 5.7 as it proceeds through the ghosting channel and the deghosting equalizer. In Fig. 5.7 (a), the original transmitted GCR is shown, while in Fig. 5.7 (b), the received GCR is depicted after passing the original GCR through the ghosting channel of Fig. 5.1 (a). Figure 5.7 (c) demonstrates the GCR signal after passing through the deghosting equalizer obtained by the proposed algorithm.



(a) The proposed GCR sequence preceded by the synchronization pulse.



(b) The ghosted GCR.
(Channel of Fig. 3 (a) is used for ghosting the GCR)



(c) The deghosted GCR sequence.

Figure 5.7: The original, ghosted, and deghosted GCRs.
(1 Sample = 0.127 μ seconds)

Note that the synchronization pulse preceding the GCR is also shown in all parts of Fig. 5.7.

The proposed system is applied to three images with different amount of details. The image of Fig. 5.8 (a) has many fine details that should be preserved while the image in Fig. 5.9 (a) has less amount of details. The image in Fig. 5.10 (a) is characterized by having almost only two gray levels, causing any degradation in the deghosting quality to be seen clearly. The application of the proposed algorithm to the three images is shown in Fig. 5.8 through Fig. 5.10. The three original images, shown in Fig. 5.8 (a), 5.9 (a), and Fig. 5.10 (a) are ghosted with the channel of Fig. 5.1 (b). The results of ghosting the images are shown in Fig. 5.8 (b), 5.9 (b), and Fig. 5.10 (b). Two noise levels are used; A relatively low SNR of 5 dB and a relatively high SNR of 20 dB are selected to corrupt the ghosted GCR in each case. The number of solutions N is taken to be 8. According to Fig. 5.2, it can be deduced that for the used channel which has a total delay between the main path and the last ghost equal to the duration of 11 samples, then an equalizer length in the range of 35 to 40 may be suitable to get a deghosted image with good subjective quality. The number of equalizer taps selected is equal to 40. In the very noisy environment having an SNR of 5 dB, the algorithm gives relatively good results with some remaining ghosts that are clearly seen in Fig. 5.8 (c), 5.9 (c), and Fig. 5.10 (c). In the less noisy environment with an SNR of 20 dB, the algorithm provides an excellent deghosting process, where all ghosts are removed with only 8 solutions. This is clearly shown in Fig. 5.8 (d), Fig. 5.9 (d), and Fig. 5.10 (d).

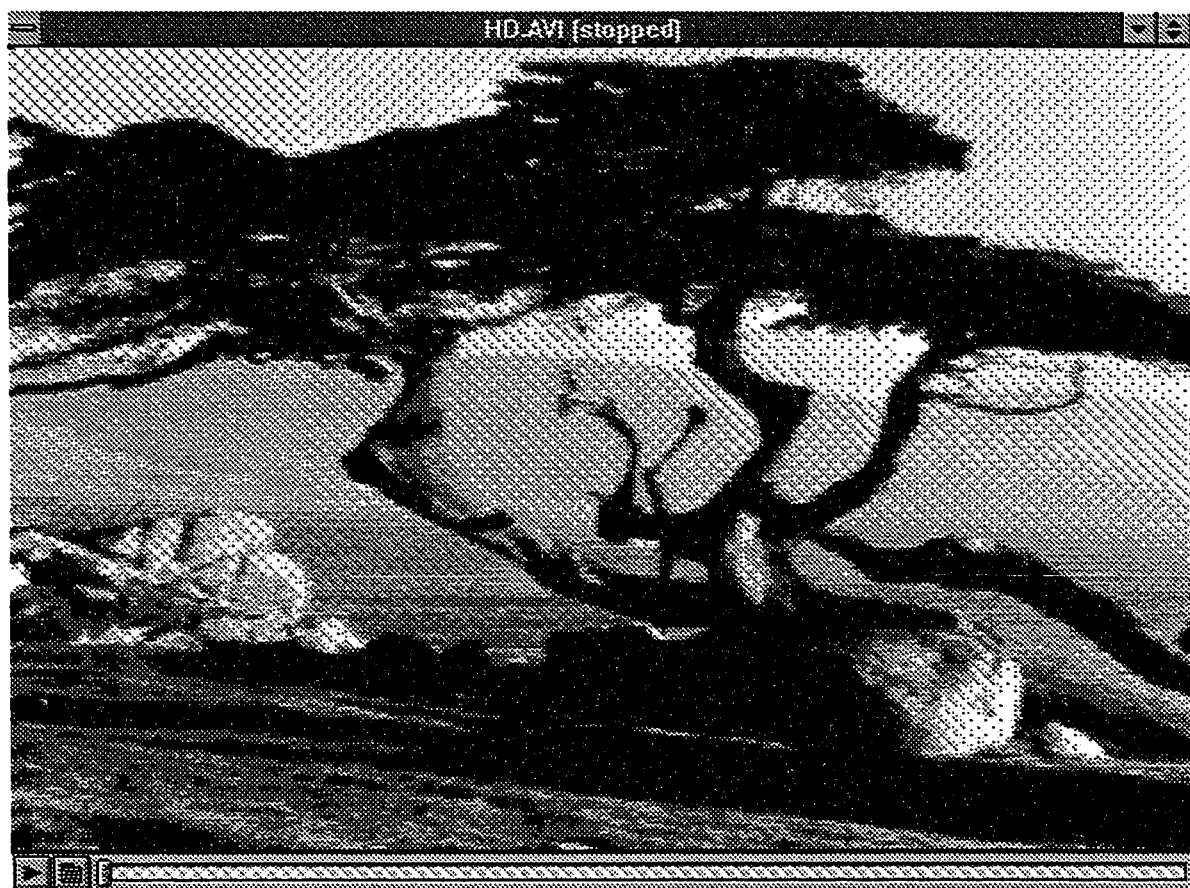


Figure 5.8 (a): High detailed original image



Figure 5.8 (b): Ghosted image with no noise added
(Channel of Fig. 5.1 (b) is used)



Figure 5.8 (c): Deghosted image
(GCR is corrupted with an SNR of 5 dB)

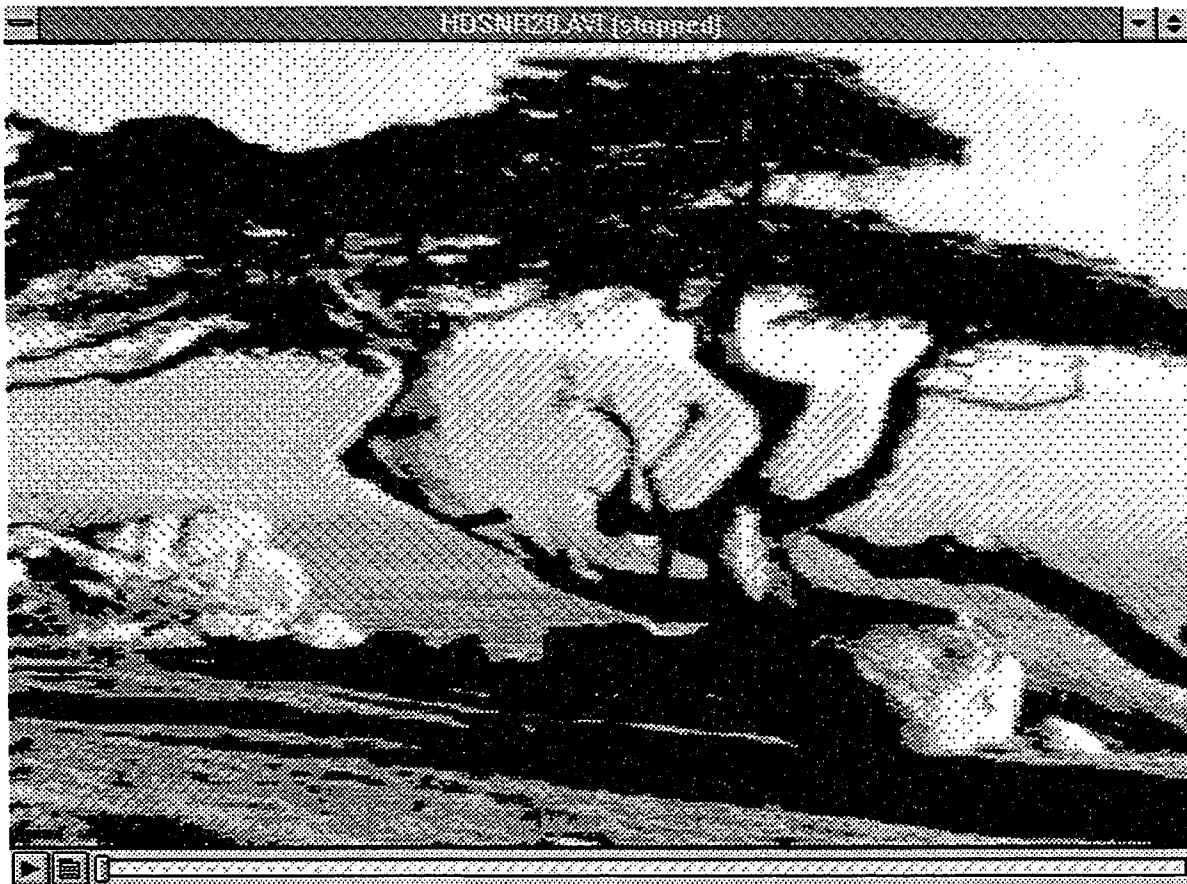


Figure 5.8 (d): Deghosted image
(GCR is corrupted with an SNR of 20 dB)

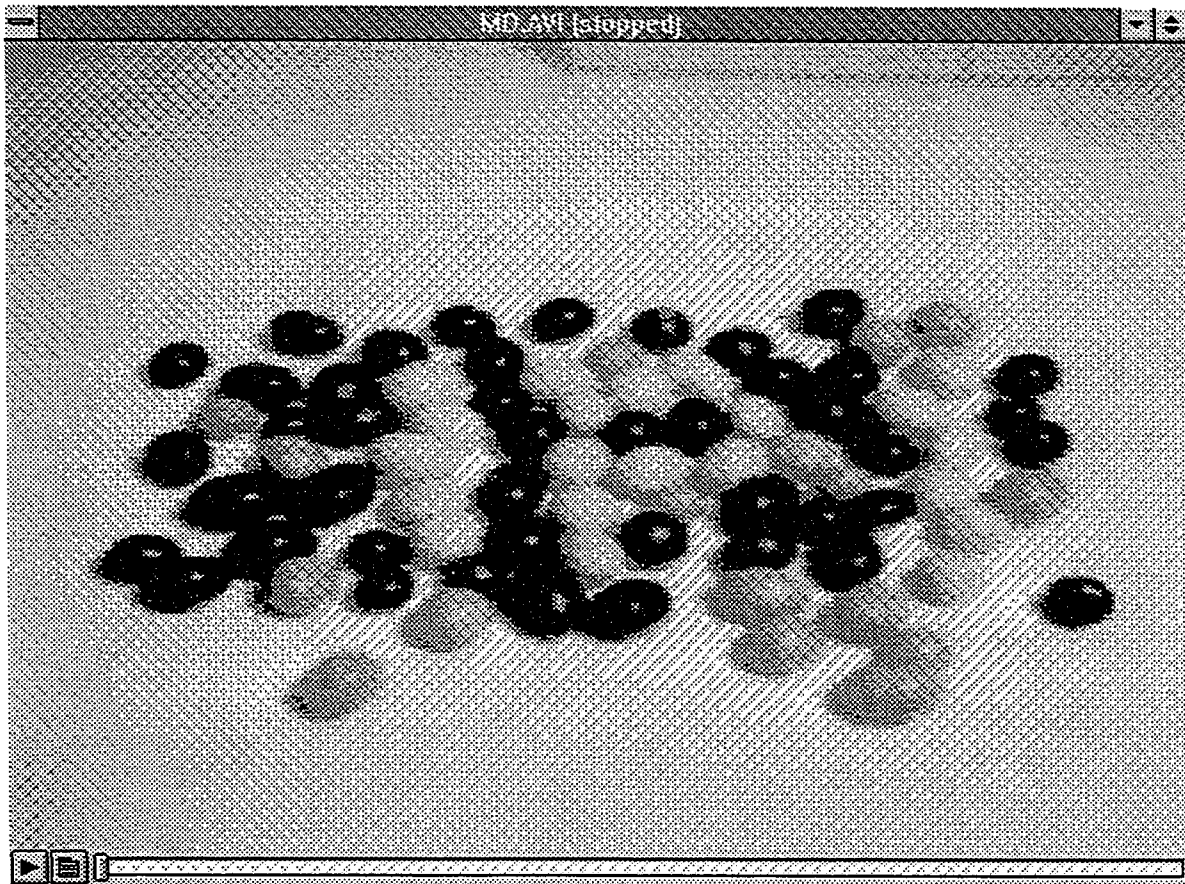


Figure 5.9 (a): Medium detailed original image

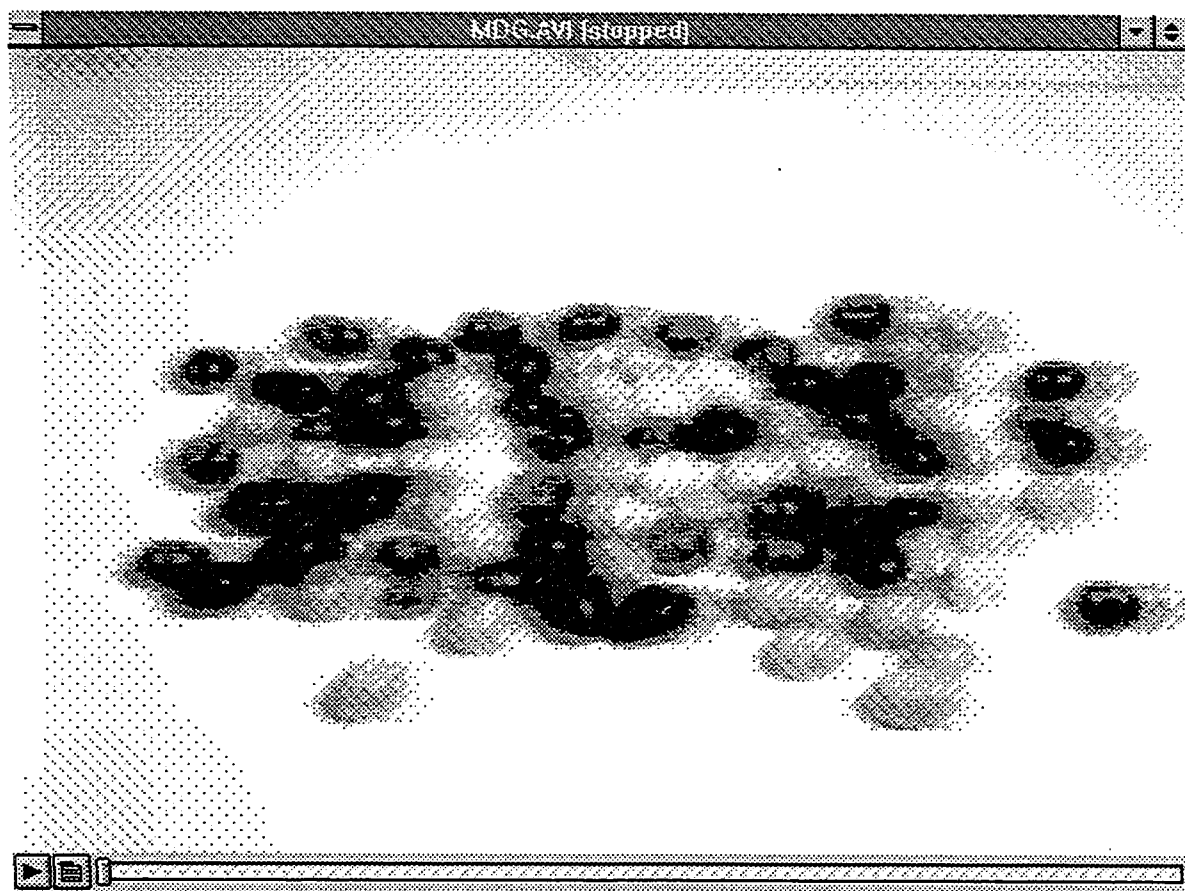


Figure 5.9 (b): Ghosted image with no noise added
(Channel of Fig. 5.1 (b) is used)

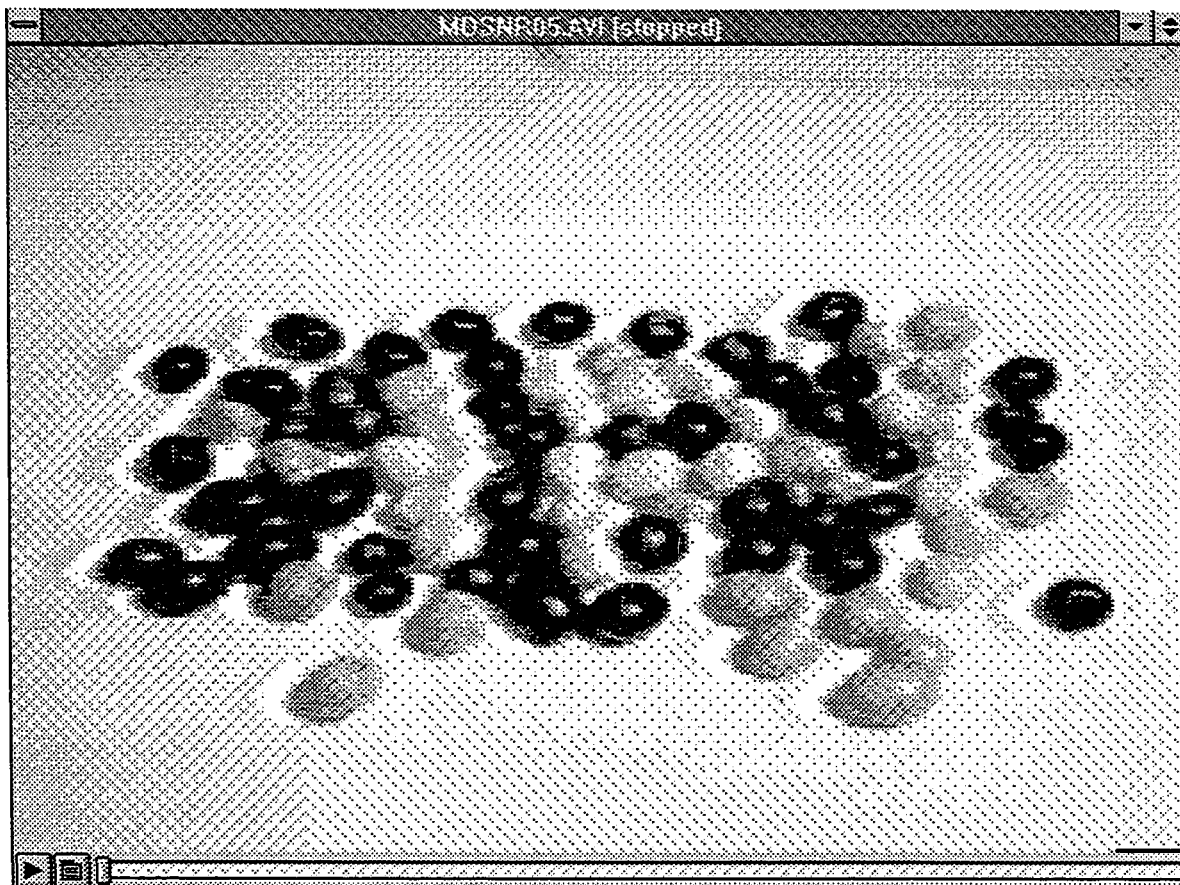


Figure 5.9 (c): Deghosted image
(GCR is corrupted with an SNR of 5 dB)

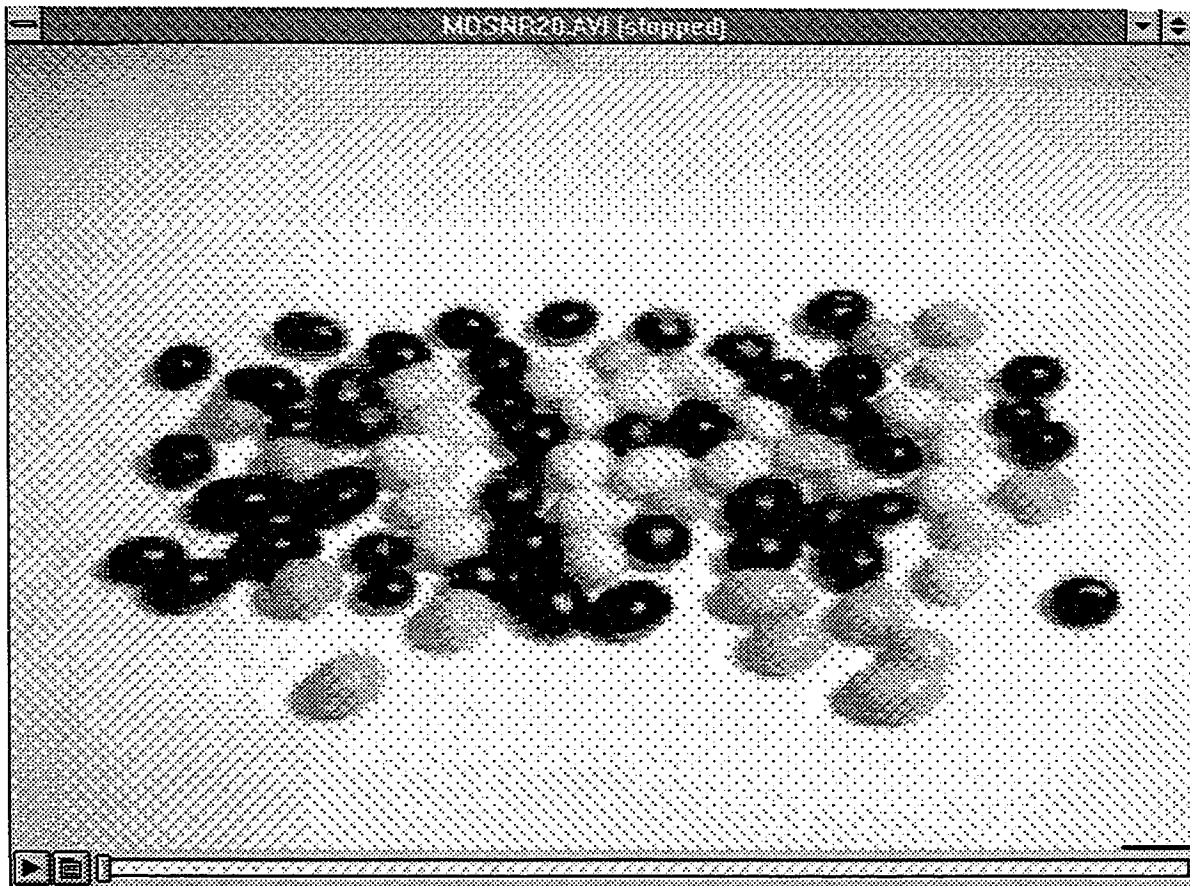


Figure 5.9 (d): Deghosted image
(GCR is corrupted with an SNR of 20 dB)

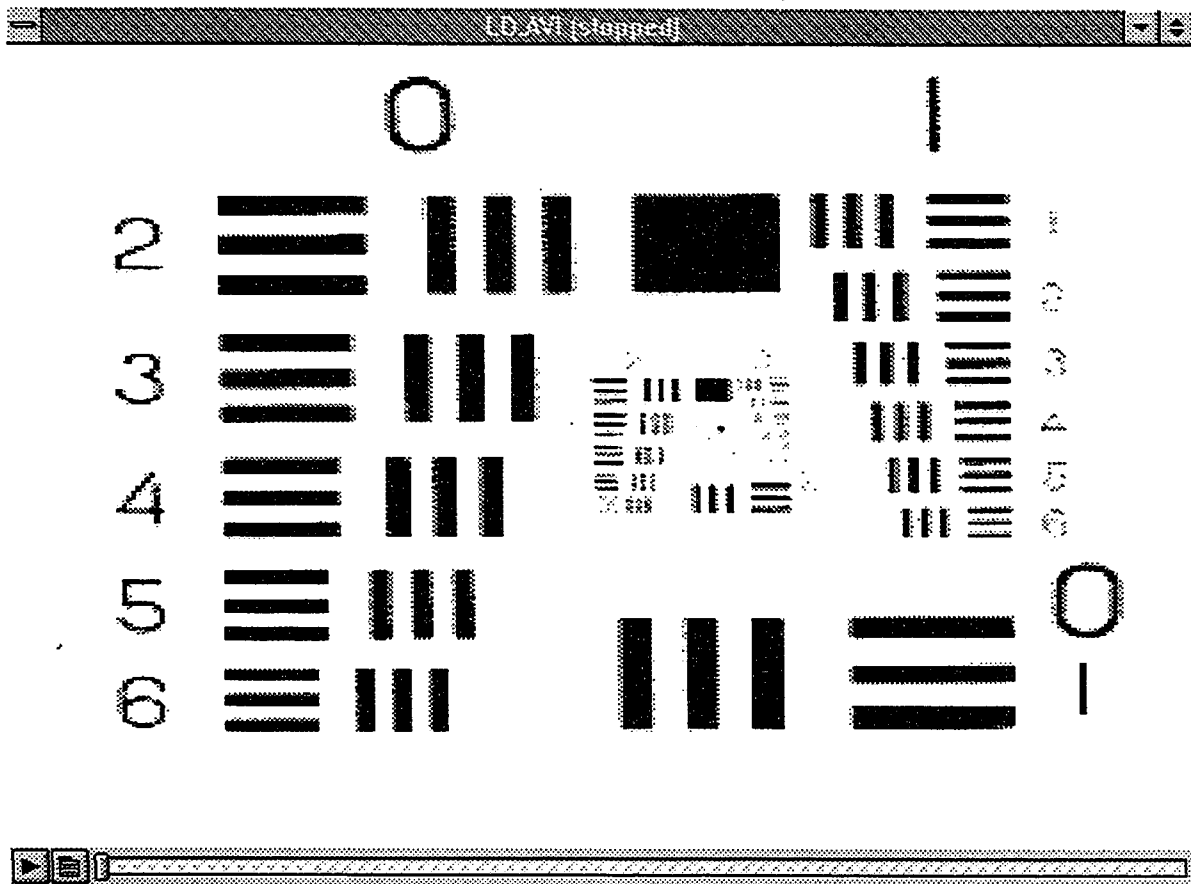


Figure 5.10 (a): Two level original image

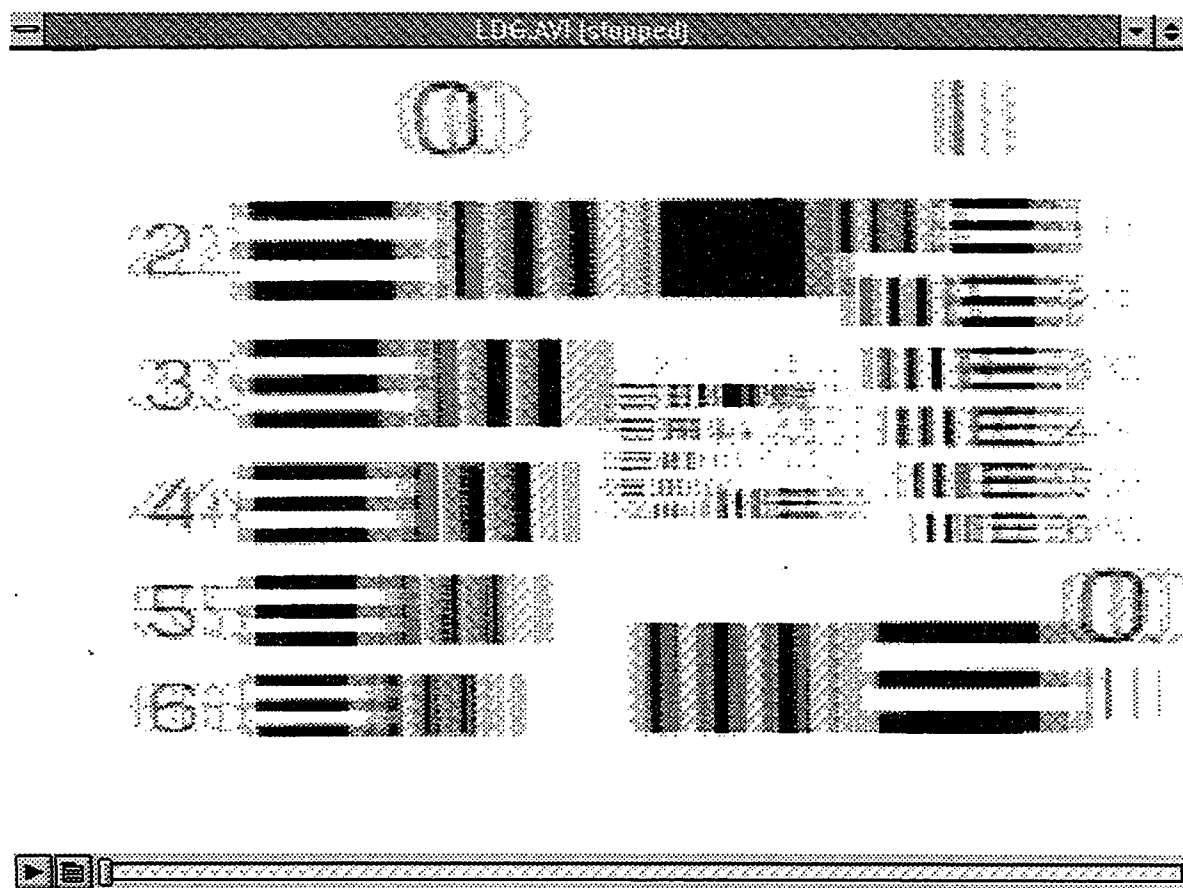


Figure 5.10 (b): Ghosted image with no noise added
(Channel of Fig. 5.1 (b) is used)

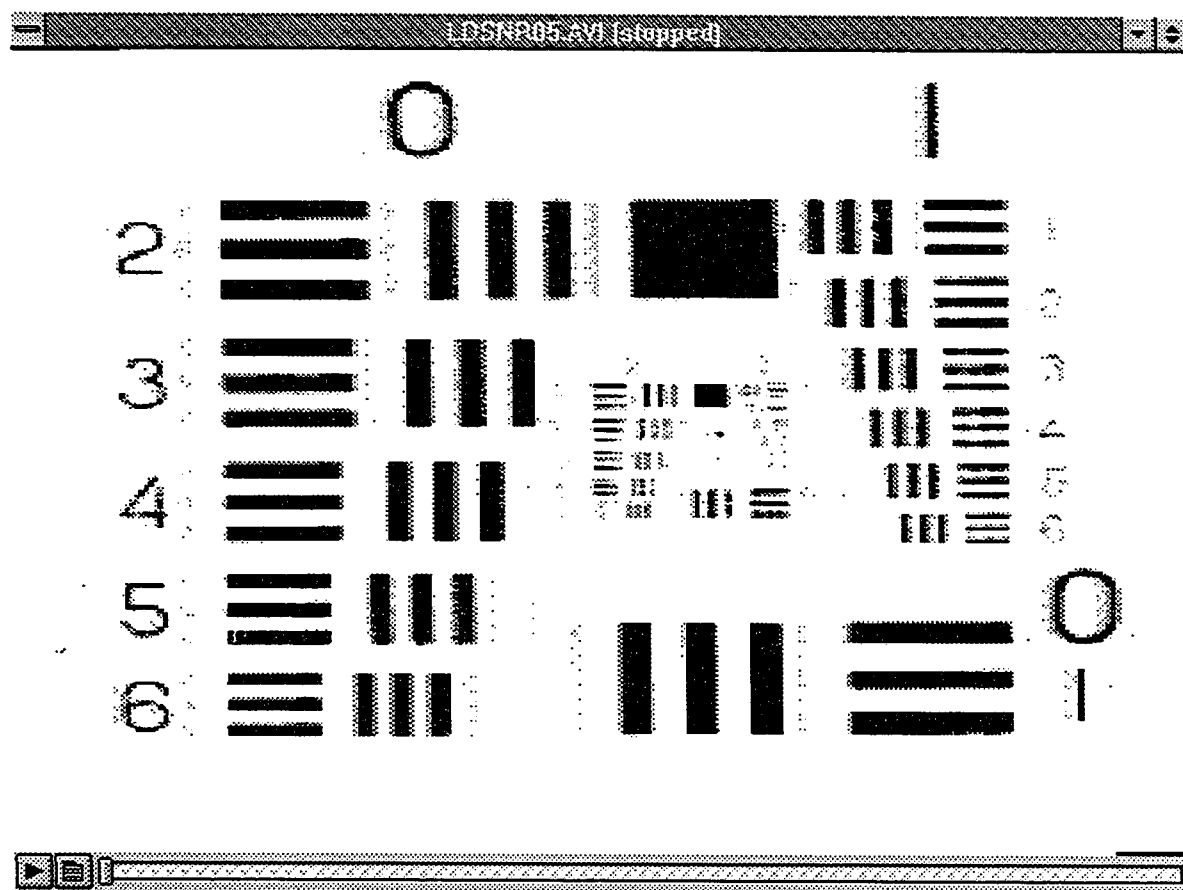


Figure 5.10 (c): Deghosted image
(GCR is corrupted with an SNR of 5 dB)

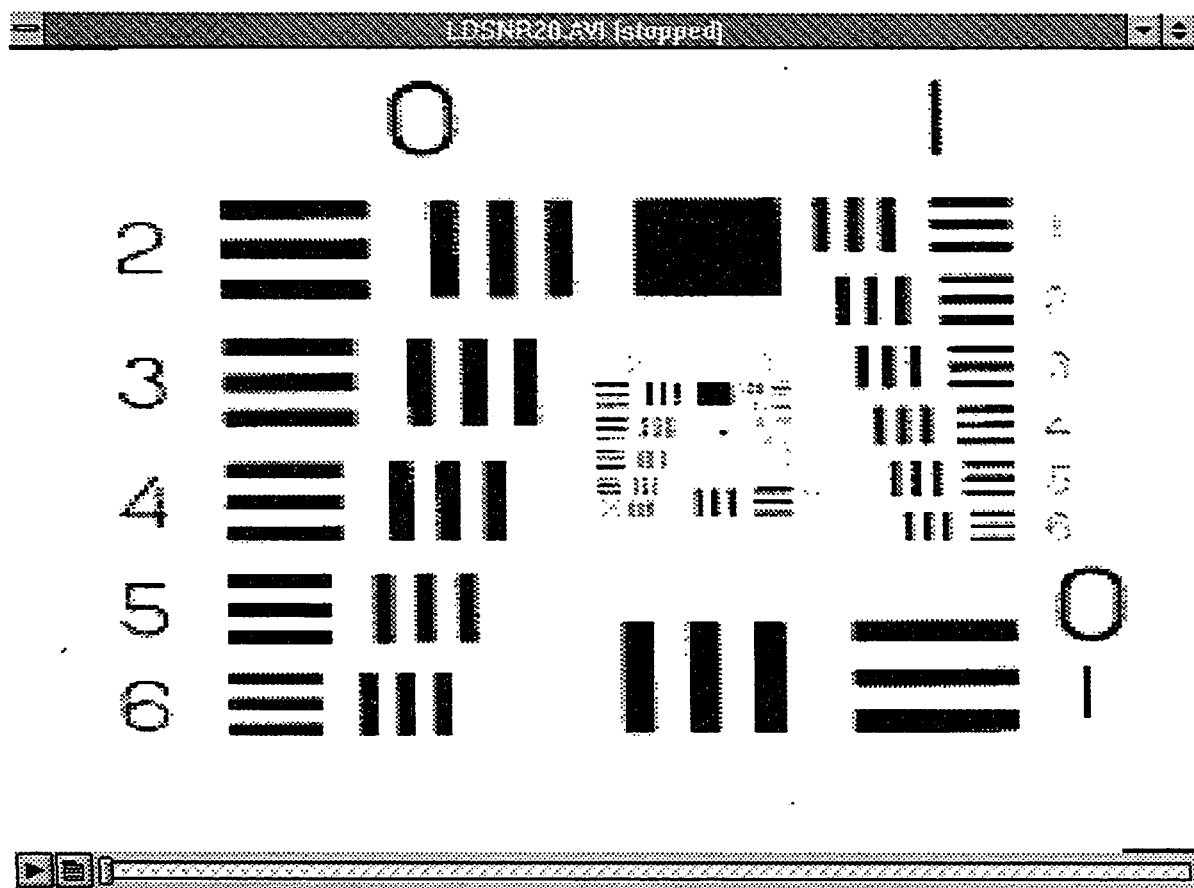


Figure 5.10 (d): Deghosted image
(GCR is corrupted with an SNR of 20 dB)

5.6 SUMMARY

From the results obtained in this chapter, it is clearly seen that the performance of the ghost canceling system proposed in this thesis gives superior deghosting results. The superiority of the algorithm is also seen when comparing the number of computations and the hardware it requires to deghost TV signals with the number of computations and hardware requirements of other deghosting algorithms as the LMS. The major cause of the superior performance and low requirements is the selection of a binary GCR that can be used to identify the ghosting channel with the maximum efficiency.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

The development of the proposed ghost canceling system was presented in Chapter 4, followed by performance evaluation of the system in Chapter 5. In this final

chapter, conclusions and recommendations for possible future research on the proposed ghost canceling algorithm, in particular, and ghost canceling, in general, are drawn.

6.1 CONCLUSIONS

In this thesis, a new GCR sequence is proposed. This GCR differs from previous GCRs in its shape and characteristics. It consists of a bipolar binary sequence with a certain order. Although this GCR is sub-optimum due to its non-flat frequency spectrum, the identification of the ghosting channel using it is seen to be remarkably good, simple, and cost effective. The channel identification using the proposed GCR requires only addition and subtraction. Time consuming operations (multiplication and division) are needed only in the equalizer setting part of the process. Other features of the proposed GCR are its simple generation using a shift register, for example, and the unnecessary generation of it at the receiver as it is the case with all previous GCRs proposed in the literature

The performance of the proposed deghosting system is studied and evaluated numerically and subjectively. The numerical evaluation reveals that the system performs very well if its parameters are properly tuned. The subjective quality of the images deghosted by this algorithm is very high for relatively low noise levels using only a limited number of computations. In relatively high noise environments, the system also performs very well by doing a small extra amount of computation only. Simulation results

demonstrate the superior performance of the proposed algorithm in comparison with one of the relatively efficient existing solutions to the TV deghosting process.

6.2 RECOMMENDATIONS FOR FUTURE STUDIES

Many research areas based on the system proposed in this thesis can be investigated in future studies. Some of the possible research topics are:

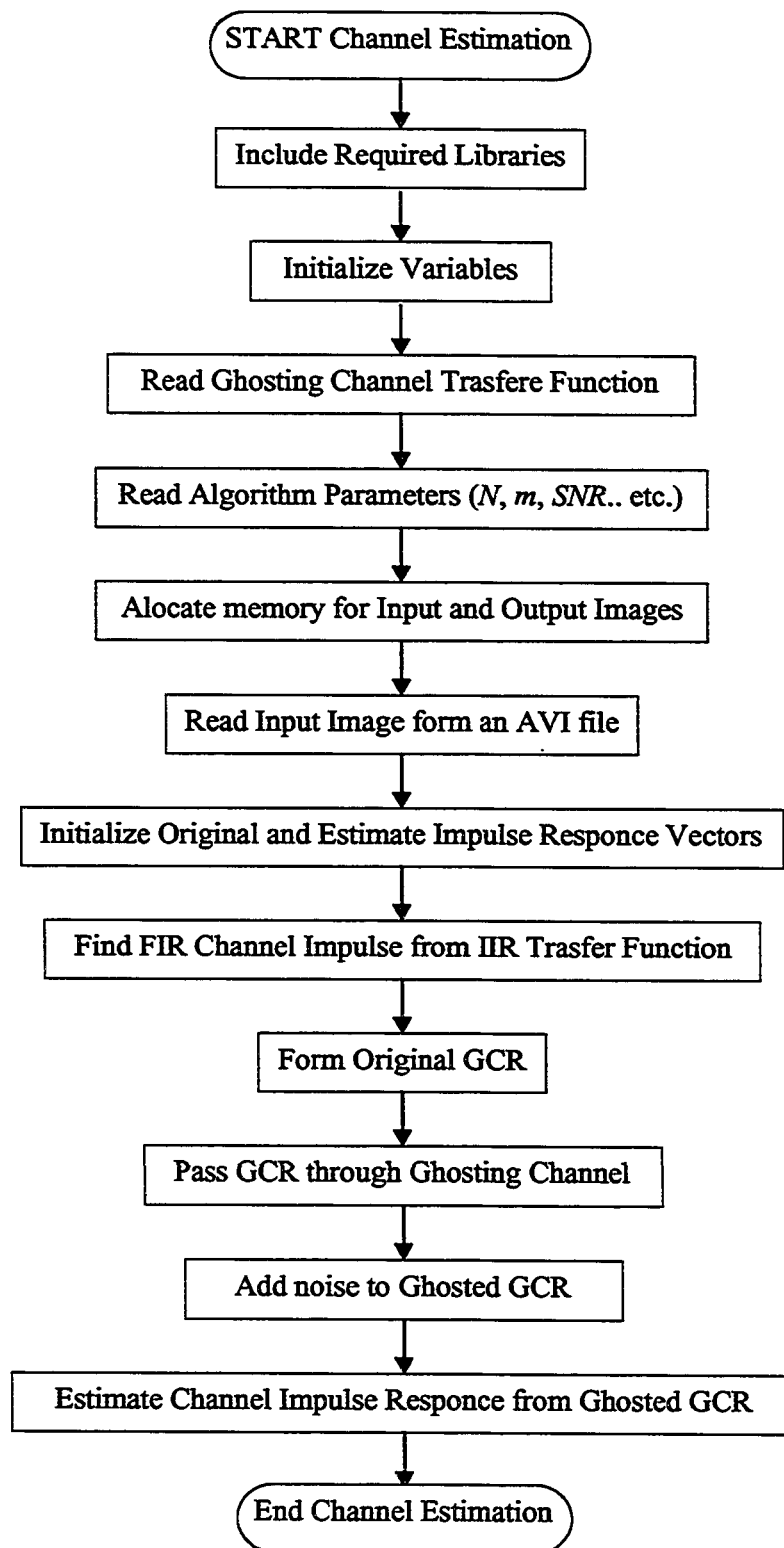
- Real time implementation and evaluation of the proposed system in a microprocessor environment.
 - The possibility of using the synchronization pulse at the end of each frame as a replacement to the proposed GCR, hence allowing the installation of this system in TVs used in all countries without the need to transmit a GCR.
 - Studying the possibility of detecting the noise level added to the ghosting channel.
 - Testing the proposed deghosting system with more complicated ghosting channels found in certain geographical regions such as near mountains or buildings.
 - Trying to implement the indirect deghosting algorithm based on the GCR proposed in this thesis.
 - Extending the proposed GCR to include complex valued waveforms for better dealing with baseband systems.
 - Incorporating the existing GCR with the recently proposed HDTV system with digital transmission.
-

Appendix A

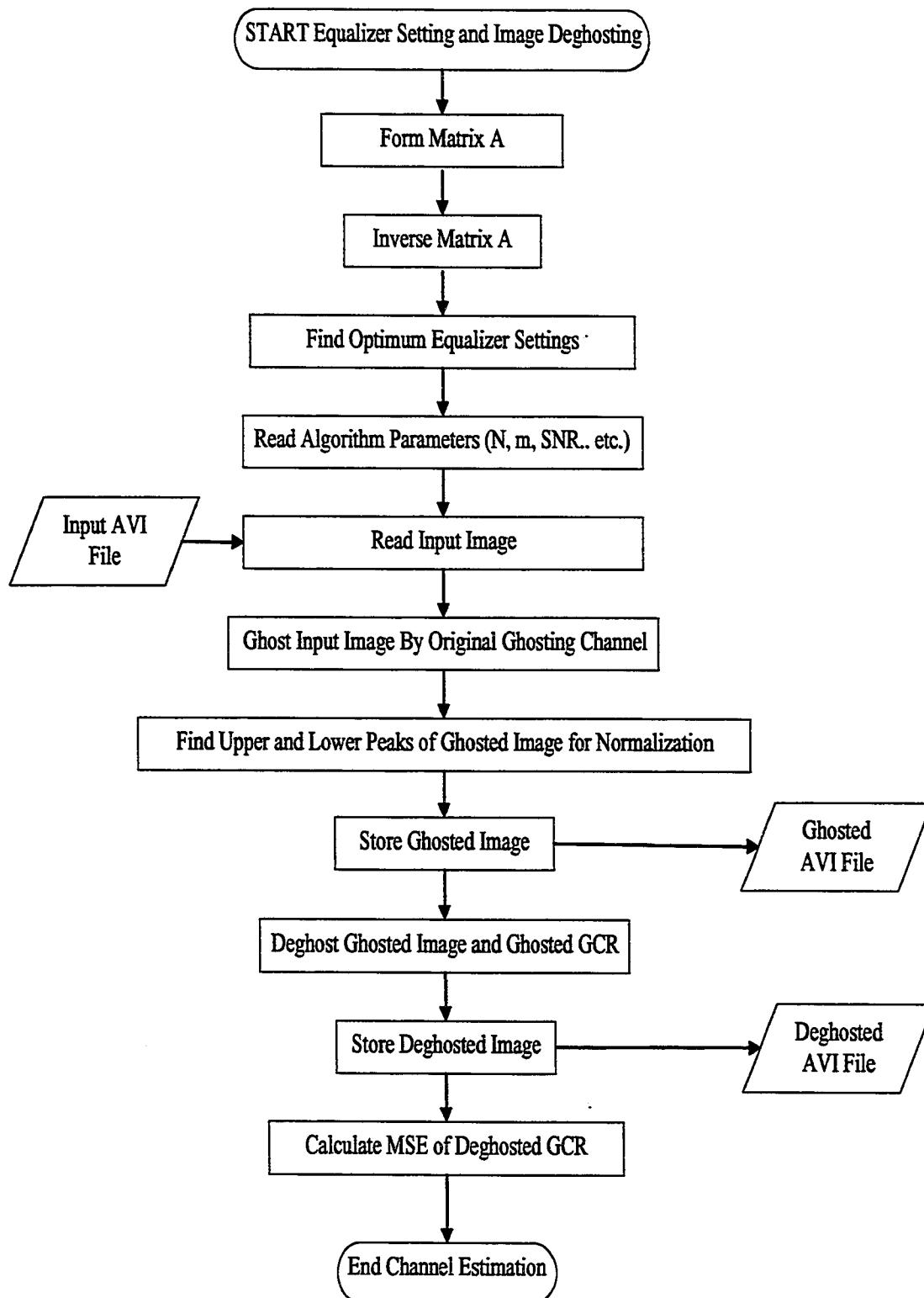
FLOWCHART OF THE SIMULATION PROGRAM

This appendix illustrates the flow chart of the simulation program. Each block in the flow chart represents a stand-alone subroutine. The Input and output points of the program are indicated. To simplify the program flow chart, it is divided into two parts. The first part is the channel estimation, and the second is the deghosting equalizer taps setting.

FLOW CHART OF CHANNEL ESTIMATION PROCESS



FLOW CHART OF EQUALIZER SETTING PROCESS



Appendix B

LISTINGS OF SIMULATION PROGRAMS

The simulation program is divided into three files. The first is the main program. This file initializes variables, allocate memory, and calls ghost canceling subroutines. The second contains the ghosting and deghosting subroutines. The third file is used for definitions, where it contains the original ghosting channel, system parameters, and subroutines declaration.

GHOST GENERATION AND CANCELLATION MAIN

SUBROUTINE

NAME OF FILE IS "GHOST.C"

```
// =====//
//                                     //
//   Ghost Generation and Cancellation Program   //
//                                     //
//   Programed by: Wajih A. Abu Al-Saud           //
//   ID #:      893014                           //
//   at:        King Fahd University of Petroleum and Minerals //
//   Date:      01 / 28 / 1996                   //
//                                     //
//                                     //
//=====//

#include <stdlib.h>           //   Include the required Difintion
#include <time.h>             //   Files and Libraries
#include <windows.h>          //
#include <avifile.h>          //   Library for AVI file managment
#include "avi_d.h"           //
#include "ghost.h"           //   Subroutines
#include "aviio.h"           //
#include <stdio.h>            //
#include <string.h>           //
#include <math.h>             //
#include <dos.h>              //
#include <malloc.h>           //

//=====//
//   Include the file containing the subroutines   //
//=====//

#include "subrout.h"
```

```
//=====//
//      Start the main subroutine and read arguments from the      //
//      command line                                              //
//=====//

void
main(int argc, char *argv[])
{

//=====//
//      Initialize Input, Ghosted, and Output Images File names    //
//=====//

char      InputFileName[100] ="Picture1.avi";
char      GhostedFileName[100] ="Picture2.avi";
char      DeghostedFileName[100] ="Picture3.avi";

//=====//
//      Define the three pointers holding the addresses of the Input, //
//      Ghosted, and Output Images.                                //
//=====//

unsigned char  huge *InputImage[3];
unsigned char  huge *GhostedImage[3];
unsigned char  huge *DeghostedImage[3];

//=====//
//      Define three variables as AVI files.                        //
//=====//

AviFile      InputAviFile;
AviFile      GhostedAviFile;
AviFile      DeghostedAviFile;

//=====//
//      Define Main program's Local Variables                      //
//=====//

int          BinarySeq[600];          // Vector storing original GCR
float        GhostedSeq[600];          // Vector storing ghosted GCR
float        TF[200];                 // Vector of original Transfer
                                           // Function
```

```

float      EstTF[200];           // Vector of estimated Transfer
                                   // Function
int        Height;              // Height of the three images
int        Width;               // Width of the three images
int        c;                   // Counter
float      UpperPeakValue;      // Maximum pixel value for
                                   // normalization
float      LowerPeakValue;      // Minimum pixel value for
                                   // normalization
float huge *A, *Ainv;           // Pointers to memory storing matrix
                                   // A and inverse of A
float      b[80], Copt[80];     // Vectros storing values of vector
                                   // b and the optimum equalizer taps
float      MSE;                 // Mean square error of estimatd
                                   // channel
int        Counter = 0;         // Counter

//=====
//      Allocate memory for the matrixes  A  and  inverse of A
//=====

      A      = (float huge *)malloc (80*80,sizeof(float));
      AInv = (float huge *)malloc (80*80,sizeof(float));

      .

//=====
//      Copying the name of input, ghosted and output images
//      from the command line to local variables
//=====

strcpy(InputFileName,argv[1]);
strcpy(GhostedFileName,argv[2]);
strcpy(DeghostedFileName,argv[3]);

//=====
//      Initialization of AVI routines
//=====

AVIFileInit();

```

```

//=====//
//   Allocating Maximum Memory of MAX_HIGHTxMAX_WIDTH for the Y, U,   //
//   and V  color planes of the input, ghosted and output images       //
//=====//

for (c=0; c<3; c++) {
    InputImage[c] = (unsigned char huge *)halloc
                    ((long)MAX_HIGHT*(long)MAX_WIDTH,1);
    GhostedImage[c] = (unsigned char huge *)halloc
                     ((long)MAX_HIGHT*(long)MAX_WIDTH,1);
    DeghostedImage[c] = (unsigned char huge *)halloc
                        ((long)MAX_HIGHT*(long)MAX_WIDTH,1);
}

//=====//
//   Initializing the data structure necessary for reading               //
//   the input image                                                     //
//=====//

InputAviFile.FileIsOpen  = FALSE;
InputAviFile.StreamIsOpen = FALSE;
InputAviFile.nFrameNum   = 0;
InputAviFile.DesiredHeight = 256;
InputAviFile.DesiredWidth  = 256;

//=====//
//   Reading the image data from the input image file into the         //
//   buffer InputImage                                                  //
//=====//

NewReadFrame(InputFileName,&InputAviFile,InputImage, FALSE);

//=====//
//   Coping input image parameters to local variables                  //
//=====//

Height = InputAviFile.ImageHeight;
Width  = InputAviFile.ImageWidth;

```

```

//=====//
//   Copying the image header from the input image to the Ghosted   //
//   image.                                                           //
//=====//

    GhostedAviFile = InputAviFile;
    GhostedAviFile.ImageHeight = Height;
    GhostedAviFile.ImageWidth = Width;
    GhostedAviFile.FileIsOpen  = FALSE;

//=====//
//   Copying the image header from the input image to the output   //
//   deghosted image.                                              //
//=====//

    DeghostedAviFile = InputAviFile;
    DeghostedAviFile.ImageHeight = Height;
    DeghostedAviFile.ImageWidth = Width;
    DeghostedAviFile.FileIsOpen  = FALSE;

/*****/
//   Start Calling the ghost canceling program subroutines         //
/*****/

//=====//
//   Initializing transfere function arrays to zero                 //
//=====//

    InitTF(TF, EstTF);

//=====//
//   Finding the Finite Impulse Responce Coef. from the transfere   //
//   function which is in the form   $N(z) / D(z)$                 //
//=====//

    FindTF(LenN, LenD, LenTF, N, D, TF);

//=====//
//   Forming the Ghost Cancelling Reference (GCR) signal to be      //
//   used to identify the channel.                                   //
//=====//

```



```

FormGCR(SolnNum, LenTF, BinarySeq);

//=====//
//  Ghosting the original GCR by passing it through the ghosting  //
//  channel.                                                         //
//=====//

GhostGCR(SolnNum, LenTF, TF, BinarySeq, GhostedSeq);

//=====//
//  Adding Gaussian Noise to the Ghosted GCR signal.               //
//=====//

NoiseGCR(SNRdB, SolnNum, LenTF, GhostedSeq);

//=====//
//  Estimating the Transfere function from the ghosted GCR.        //
//=====//

EstemateTF(SolnNum, LenTF, GhostedSeq, EstTF);

//=====//
//  Formint the matrix "A".                                         //
//=====//

FormA(SNRdB, EqualizerSize, LenTF, EstTF, A);

//=====//
//  Finding the Inverse of the matrix  "A".                         //
//=====//

InverseA(EqualizerSize, A, AInv);

//=====//
//  Finding the optimaum equalizer queaffecients                  //
//=====//

FindEqualizer(EqualizerSize, LenTF, EstTF, COpt, AInv, b);

```

```

//=====//
// Finding the Upper and Lower peak Pixel values to be //
// used in normalization for display purposes only to //
// avoid wrap around in integer values. //
//=====//

    FindPeaks(LenTF, Height, Width, InputImage, TF, &UpperPeakValue,
              &LowerPeakValue);

//=====//
// Ghosting the input image and Normalized the resulting pixel //
// value then storing it in the output image //
//=====//

    GhostImage(LenTF, Height, Width, InputImage, GhostedImage, TF,
              UpperPeakValue, LowerPeakValue);

//=====//
// Deghosting the ghosted image //
//=====//

    DeghostImage(EqualizerSize, LenTF, Height, Width, GhostedImage,
                 DeghostedImage, COpt, UpperPeakValue, LowerPeakValue);

//=====//
// Writing the data of the output images into the output image //
// files. //
//=====//

    GhostedAviFile.nFrameNum = 0;
    NewWriteFrame(GhostedFileName, &GhostedAviFile, GhostedImage, FALSE);
    DeghostedAviFile.nFrameNum = 0;
    NewWriteFrame(DeghostedFileName, &DeghostedAviFile,
                 DeghostedImage, FALSE);

//=====//
// Closing all open AVI file and terminating AVI routines //
//=====//

    CloseAVIFile(&GhostedAviFile);
    CloseAVIFile(&DeghostedAviFile);

```

```

    AVIFileExit();

//=====//
//    Findign the mean square error in the estimated transfere    //
//    function and printing it.                                     //
//=====//

    MSE = 0;
    for (i = 0; i < LenTF; i ++)
    {
        MSE += (float)pow((EstTF[i] - TF[i]),2);
    }
    MSE = MSE / LenTF;

    printf("The mean square error in the estimated ");
    printf("channel TF is =   %8f  \n" ,MSE);
}

//=====//
//    Closing the main subroutine.                                  //
//=====//

```

GHOST GENERATION AND CANCELLATION

SUBROUTINES

NAME OF FILE IS "SUBROUT.H"

```
//=====//
//
//   Ghost Generation and Cancelation Program
//
//   Programed by: Wajih A. Abu Al-Saud
//   ID #:      893014
//   at:      King Fahd University of Petroleum and Minerals
//   Date:      01 / 28 / 1996
//
//=====//

//=====//
//   Initializing transfere function arrayes to zero
//=====//

void
InitTF(float      *TF,
       float      *EstTF)

{
  int   i;

  for (i = 0; i < 200; i++)
  {
    TF[i] = 0;
    EstTF[i] = 0;
  }
}

//=====//
//   Finding the Finite Impulse Responce Coef. from the transfere
//   function which is in the form  $N(z) / D(z)$ 
//=====//
```

```

void
FindTF(int      LenN,
        int      LenD,
        int      LenTF,
        float    *N,
        float    *D,
        float    *TF)

{
int      i, j;
float    Temp[300];

    for (i = 0; i < LenTF; i++)
    {
        TF[i] = 0;
        Temp[i] = 0;
    }
    for (i = 0; i < LenN; i++)
        Temp[i] = N[i];
    for (i = 0; i < LenTF; i++)
    {
        TF[i] = Temp[i] / D[0];
        for (j = i; j < i + LenD; j++)
            Temp[j] = Temp[j] - TF[i] * D[j-i];
    }
}

//=====//
//    Forming the Ghost Cancelling Reference (GCR) signal to be    //
//    used to identify the channel.                                //
//=====//

void
FormGCR(int      SolnNum,
        int      LenTF,
        int      *BinarySeq)

{
int      k;

    for (k = 0; k <= ((SolnNum + 1) * (LenTF - 1) + SolnNum - 1); k++)
    {

```

```

        BinarySeq[k] = (int)pow(-1,(int)((k+LentTF+1) / (LentTF)));
    }
}

//=====//
//   Ghosting the original GCR by passing it through the ghosting   //
//   channel.                                                         //
//=====//

void
GhostGCR(int    SolnNum,
         int     LentTF,
         float   *TF,
         int     *BinarySeq,
         float   *GhostedSeq)

{
    int         i, k;
    float       PixelValue;

    for (i = LentTF - 1; i <= ((SolnNum + 1) *
        (LentTF - 1) + SolnNum - 1); i++)
    {
        PixelValue = 0;
        for (k = 0; k < LentTF; k++)
        {
            PixelValue += BinarySeq[i-k] * TF[k];
        }
        GhostedSeq[i] = PixelValue;
    }
}

//=====//
//   Adding Gaussian Noise to the Ghosted GCR signal.               //
//=====//

void
NoiseGCR(float   SNRdB,
         int      SolnNum,
         int      LentTF,
         float    *GhostedSeq)

```

```

{
int      i;
float    NoiseStdDiv;

// Seed the random number genrator with the value 1 to get consistant
// results in all program executions.

    srand(1);
    NoiseStdDiv = (float) sqrt(1 / (pow(10, (SNRdB / 10))));
    for (i = 0; i <= ((SolnNum + 1) *
        (LentTF - 1) + SolnNum - 1); i++)
    {
        GhostedSeq[i] += (float) (NoiseStdDiv *
            sqrt(-2.0 * log((rand()+1) / 32765.0)) *
            cos(2 * 3.14159 * rand() / 32765.0));
    }
}

//=====//
//  Estimating the Transfere function from the ghosted GCR.      //
//=====//

void
EstemateTF(int      SolnNum,
           int      LentTF,
           float    *GhostedSeq,
           float    *EstTF)
{
int      i, j;

    EstTF[0] = 0;
    for (j = 0; j <= SolnNum - 1; j++)
    {
        EstTF[0] += (float) ( 0.5 / SolnNum * pow(-1,j) *
            (GhostedSeq[LentTF - 1 + j * LentTF] +
            GhostedSeq[2*(LentTF-1) + j * LentTF]));
    }

    for (i = 1; i < LentTF; i++)
    {

```

```

        EstTF[i] = 0;
        for (j = 0; j <= SolnNum - 1; j ++)
        {
            EstTF[i] += (float) ( 0.5 / SolnNum * pow(-1,j) *
                (GhosedSeq[LentTF - 1 + j * LentTF + i] -
                GhosedSeq[(LentTF-1) + j * LentTF + i - 1]));
        }
    }
}

//=====//
//  Formint the matrix "A".                                //
//=====//

void
FormA(float    SNRdB,
      int      EqualizerSize,
      int      LentTF,
      float    *EstTF,
      float    *A)

{
    int    i, j, k;
    float  NoiseStdDiv;

    NoiseStdDiv = (float) sqrt(1 / (pow(10,(SNRdB / 10))));
    for (i=0; i < EqualizerSize; i ++)
    {
        for (j=0; j < EqualizerSize; j ++)
        {
            *(A+i*EqualizerSize+j) = 0;
            if (abs(i-j) < LentTF)
            {
                for (k=0; k < LentTF - abs(i - j); k ++)
                {
                    *(A+i*EqualizerSize+j) += EstTF[k] *
                        EstTF[k+ abs(i-j)];
                }
            }
        }
    }
}

```



```

//=====//
// Finding the Inverse of the matrix "A". //
//=====//

void
InverseA(int    EqualizerSize,
         float  *A,
         float  *AInv)

{
    int    i, j, k;
    float  factor;

    for (i=0; i < EqualizerSize; i++)
    {
        for (j = 0; j < EqualizerSize; j++)
        {
            *(AInv + i * EqualizerSize+j) = 0;
        }
    }

    for (i = 0; i < EqualizerSize; i++)
    {
        *(AInv + i * EqualizerSize + i) = 1;
    }

    for (i = 0; i < EqualizerSize - 1; i++)
    {
        for (j = i + 1; j < EqualizerSize; j++)
        {
            factor = *(A + j * EqualizerSize + i) /
                      *(A + i * EqualizerSize + i);
            for (k = 0; k < EqualizerSize; k++)
            {
                *(A + j * EqualizerSize + k) -= factor *
                                                  *(A + i * EqualizerSize + k);
                *(AInv + j * EqualizerSize + k) -= factor *
                                                  *(AInv + i * EqualizerSize + k);
            }
        }
    }
}

```

```

for (i = EqualizerSize - 1 ; i > 0; i --)
{
    for (j = i - 1; j >= 0; j --)
    {
        factor = *(A + j * EqualizerSize + i) /
            *(A + i * EqualizerSize + i);
        for (k = 0; k < EqualizerSize; k++)
        {
            *(A + j * EqualizerSize + k) -= factor *
                *(A + i * EqualizerSize + k);
            *(AInv + j * EqualizerSize + k) -= factor *
                *(AInv + i * EqualizerSize + k);
        }
    }
}

for (i = 0; i < EqualizerSize; i ++)
{
    for (j = 0; j < EqualizerSize; j++)
    {
        *(AInv + i * EqualizerSize + j) =
            *(AInv + i * EqualizerSize + j) /
            *(A + i * EqualizerSize + i);
    }
    *(A + i * EqualizerSize + i) = 1;
}

}

//=====//
//    Finding the optimaum equalizer queaffecients    //
//=====//

void
FindEqualizer(int    EqualizerSize,
               int    LenTF,
               float  *EstTF,
               float  *COpt,
               float  *AInv,
               float  *b)

```

```

{
int    i, j;

    for (i = 0; i < EqualizerSize; i++)
    {
        if (i < LenTF) b[i] = EstTF[LenTF-i-1];
        else b[i] = 0;
    }

    for (i = 0; i < EqualizerSize; i++)
    {
        COpt[i] = 0;
        for (j = 0; j < EqualizerSize; j++)
        {
            COpt[i] += *(AInv + i * EqualizerSize + j) * b[j];
        }
    }
}

//=====//
//    Finding the Upper and Lower peak Pixel values to be    //
//    used in normalization for display purposes only to    //
//    avoid wrap around in integer values.                  //
//=====//

void
FindPeaks(int    LenTF,
          int    Height,
          int    Width,
          unsigned char *InputImage[3],
          float   *TF,
          float   *UpperPeakValue,
          float   *LowerPeakValue)

{
int      k;
int long w;
float    PixelValue;

    *UpperPeakValue = 0;
    *LowerPeakValue = 255;
    for (w = LenTF; w < (long int)(Height*1.0 * Width); w++)

```

```

        {
            PixelValue = 0;
            for (k = 0; k < LenTF; k++)
            {
                PixelValue += *(InputImage[0]+(long)w-k) * TF[k];
            }
            if (PixelValue > *UpperPeakValue)
                *UpperPeakValue = PixelValue;
            if (PixelValue < *LowerPeakValue)
                *LowerPeakValue = PixelValue;
        }
    }

//=====//
//  Ghosting the input image and Normalized the resulting pixel    //
//  value then storing it in the output image                      //
//=====//

void
GhostImage(int      LentF,
           int      Height,
           int      Width,
           unsigned char *InputImage[3],
           unsigned char *GhosedImage[3],
           float     *TF,
           float     UpperPeakValue,
           float     LowerPeakValue)

{

    int      i, j, k;
    int      long  w;
    float     PixelValue;

    for (w = LentF; w < (long int) (Height*1.0 * Width); w++)
    {
        PixelValue = 0;
        for (k = 0; k < LentF; k++)
        {
            PixelValue += *(InputImage[0]+(long)w-k) * TF[k];
        }
        *(GhosedImage[0]+(long)w) =

```

```

        (char) (255.0 / (UpperPeakValue - LowerPeakValue)
        * (PixelValue - LowerPeakValue));
    }
    for (i = 0; i < Height / 2; i++)
    {
        for (j = 0; j < Width / 2; j++)
        {
            *(GhostedImage[1]+(long)i*Width / 2+(long)j) = 128;
            *(GhostedImage[2]+(long)i*Width / 2+(long)j) = 128;
        }
    }
}

//=====//
//    Deghosting the ghosted image                //
//=====//

void
DeghostImage(int          EqualizerSize,
             int          LentF,
             int          Height,
             int          Width,
             unsigned char *GhostedImage[3],
             unsigned char *DeghostedImage[3],
             float        *COpt,
             float        UpperPeakValue,
             float        LowerPeakValue)

{
    int      i, j, k;
    int long w;
    float    Temp;
    float    PixelValue;

    Temp = 0;
    for (w = EqualizerSize; w < (long int)(Height*1.0 * Width); w++)
    {
        PixelValue = 0;
        for (k = 0; k < EqualizerSize; k++)
        {
            PixelValue += *(GhostedImage[0]+(long)w-k) *
                           COpt[k];

```

```

    }
    if (((UpperPeakValue - LowerPeakValue) / 255.0 *
        PixelValue + LowerPeakValue) > 255)
        *(DeghostedImage[0]+(long)w- LentTF+1) = 255;
    else if (((UpperPeakValue - LowerPeakValue) / 255.0 *
        PixelValue + LowerPeakValue) < 0)
        *(DeghostedImage[0]+(long)w-LentTF+1) = 0;
    else
        *(DeghostedImage[0]+(long)w-LentTF+1) =
            (char) ((UpperPeakValue - LowerPeakValue) /
                255.0 * PixelValue + LowerPeakValue);
    }

    for (i = 0; i < Height / 2; i++)
    {
        for (j = 0; j < Width / 2; j++)
        {
            *(DeghostedImage[1]+(long)i*Width / 2+(long)j) = 128;
            *(DeghostedImage[2]+(long)i*Width / 2+(long)j) = 128;
        }
    }

}

//=====//
// Find the mean square error in the between the original and //
// Deghosted images //
//=====//

float
FindMSE(int          EqualizerSize,
        int          LentTF,
        int          Height,
        int          Width,
        unsigned char *InputImage[3],
        unsigned char *DeghostedImage[3])

{
    int  long  w, counter;
    float  MSE;

```

```
counter = 0;
MSE = 0;

for (w = EqualizerSize - LenTF + 1; w < (long int)(Height*1.0 *
    Width - LenTF + 1); w++)
{
    counter += 1;
    MSE += (float)pow((* (DeghostedImage[0] + (long)w) -
        * (InputImage[0] + (long)w)), 2);
}
return (MSE / counter);
}
```

GHOST GENERATION AND CANCELLATION

DEFINITION FILE

NAME OF FILE IS "GHOST.H"

```
// =====//
//
//   Ghost Generation and Cancellation Program
//
//   Programed by: Wajih A. Abu Al-Saud
//   ID #:          893014
//   at:           King Fahd University of Petroleum and Minerals
//   Date:         01 / 28 / 1996
//
// =====//

//=====//
//   Define the maximum height and width as 512 * 512 pixels
//=====//

#define MAX_HEIGHT 512
#define MAX_WIDTH 512

//=====//
//   Define SYSTEM PARAMETERS and GHOSTING CHANNEL TRANSFERE
//   FUNCTION
//=====//

int  LenN = 20;    // Length of N(z)    ==>          N(z)
int  LenD = 20;    // Length of D(z)    ==>          H(z) = -----
int  LenTF = 18;   // Length of channel TF H(z)          D(z)
                        // starting from (0) to (n = LenTF - 1)
int  SolnNum = 8;  // Number of solutions or averagings N.
int  EqualizerSize = 40; // Number of taps in the Equalizer m.

//=====//
//   Define the Numerator of the Ghosting channel Transfere
//   function as N(z) = a(0) + a(1) z^(-1) + ... a(i) z^(-i).
//=====//
```



```

float      N[20] =      {(float)0,(float)0,(float)0.3,(float)0,(float)0,
                          (float)0,(float)1,(float)0,(float)0,(float)0,
                          (float)0,(float)-0.1,(float)0.4,(float)-0.1,
                          (float)0,(float)0,(float)0,(float)0.3,(float)0,
                          (float)0};

//=====//
//   Define the Denominator of the Ghosting channel Transfere   //
//   function as  $D(z) = b(0) + b(1) z^{-1} + \dots b(j) z^{-j}$ .   //
//=====//

float      D[20] =      {(float)1,(float)0,(float)0,(float)0,(float)0,
                          (float)0,(float)0,(float)0,(float)0,(float)0,
                          (float)0,(float)0,(float)0,(float)0,(float)0,
                          (float)0,(float)0,(float)0,(float)0,(float)0};

float      SNRdB = (float)5; // Specify the signal power to noise
                          // power ration in dB's.

//=====//
//   Define the Subroutines used in the ghosting and deghosting //
//   process.                                                    //
//=====//

void
InitTF(float      *TF,
       float      *EstTF);

void
FindTF(int      LenN,
       int      LenD,
       int      LenTF,
       float     *N,
       float     *D,
       float     *TF);

void
FormGCR(int      SolnNum,
        int      LenTF,
        int      *BinarySeq);

```

```

void
GhostGCR(int      SolnNum,
          int      LenTF,
          float    *TF,
          int      *BinarySeq,
          float    *GhostedSeq);

void
NoiseGCR(float    NoiseVar,
          int      SolnNum,
          int      LenTF,
          float    *GhostedSeq);

void
EstimateTF(int      SolnNum,
            int      LenTF,
            float    *GhostedSeq,
            float    *EstTF);

void
FormA(float    NoiseVar,
       int      EqualizerSize,
       int      LenTF,
       float    *EstTF,
       float    *A);

void
InverseA(int      EqualizerSize,
          float    *A,
          float    *AInv);

void
FindEqualizer(int      EqualizerSize,
               int      LenTF,
               float    *EstTF,
               float    *COpt,
               float    *AInv,
               float    *b);

void
FindPeaks(int      LenTF,
           int      Height,

```

```

    int      Width,
    unsigned char *InputImage[3],
    float     *TF,
    float     *UpperPeakValue,
    float     *LowerPeakValue);

```

```
void
```

```

GhostImage(int      LenTF,
            int      Height,
            int      Width,
            unsigned char *InputImage[3],
            unsigned char *GhostedImage[3],
            float     *TF,
            float     UpperPeakValue,
            float     LowerPeakValue);

```

```
void
```

```

DeghostImage(int      EqualizerSize,
              int      LenTF,
              int      Height,
              int      Width,
              unsigned char *GhostedImage[3],
              unsigned char *DeghostedImage[3],
              float     *COpt,
              float     UpperPeakValue,
              float     LowerPeakValue);

```

```
float
```

```

FindMSE(int      EqualizerSize,
         int      LenTF,
         int      Height,
         int      Width,
         unsigned char *InputImage[3],
         unsigned char *DeghostedImage[3]);

```

Appendix C

NOMENCLATURE

N_{in}	input noise power
N_{out}	output noise power
U/D	ratio of undesired signal voltage to desired signal voltage
M	number of taps of filter
$c(t)$	coefficient vector at time t
$x(t), y(t)$	received data vectors

$d(t)$	desired value at time t
μ	constant adaptation step size
$\alpha(t)$	automatically adjusted step size at time t
$p(t)$	cross-correlation vector
$R(t)$	auto-correlation matrix
T_i	delay of the i th channel tap coefficient
f_i	i th channel tap coefficient
\hat{f}_i	the estimated i th channel tap coefficient
c_i	i th tap coefficient of the equalizer
m	number of equalizer taps
$f(z)$	channel impulse response
F	vector of channel tap coefficients
$h(z)$	equalizer impulse response
a_k	transmitted data sequence
v_k	noiseless received sequence
\hat{a}_k	deghosted received sequence
r_k	noisy received sequence
w_k	additive noise sequence
$n+1$	channel dispersion
N	number of calculated solutions
V	noiseless received data vector
R	noisy received data vector

$E(\cdot)$	expectation operator
σ_n^2	noise power
C_{opt}	optimum equalizer tap coefficient vector
V_{GCR}	waveform of the GCR
T	sampling period
$\mathfrak{F}(\cdot)$	Fourier transform operator
MSE	mean square error between transmitted and deghosted sequences
f_e	channel coefficient error
SNR	signal power to noise power
x	forgetting factor

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Vita

Wajih Abdul-Elah Abu Al-Saud

Born in Saihat, Saudi Arabia in 1971

**Received Bachelor's degree in Electrical Engineering from King Fahd University of
Petroleum and Minerals, Dhahran, Saudi Arabia in June 1994.**

**Completed Master's degree requirements at King Fahd University of Petroleum and
Minerals in June 1996.**
